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SUPERCONDUCTING ELECTRIC MACHINES FOR SHIP PROPULSION.(U)
FEB 77 J L KIRTLEY, J L SMITH

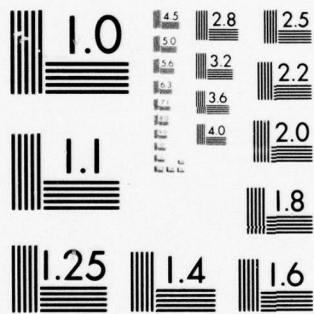
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FINAL REPORT
TO
OFFICE OF NAVAL RESEARCH

SUPERCONDUCTING ELECTRIC MACHINES
FOR SHIP PROPULSION

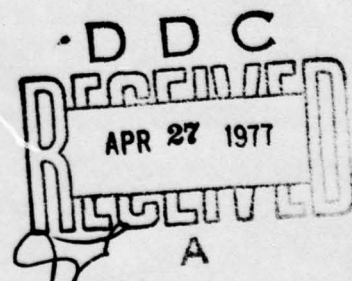
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From
✓ School of Engineering
Massachusetts Institute of Technology

14 February 1977

James L. Kirtley, Jr.
Joseph L. Smith, Jr.



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Block 20. Abstract (continued)

while experimental models were constructed of the last two. Preliminary designs were completed for each of the five machines for an appropriate ship propulsion application. In addition a theoretical study of the refrigeration requirements for AC superconducting machines was performed.

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I. Introduction

This report summarizes the result of research on "Superconducting Electric Machines for Ship Propulsion" under Contract No. N0014-67-A-0204-0068, June 27, 1972 to December 31, 1974 and Contract No. N0014-75-C-0497, January 1, 1975 to December 31, 1976.

The work under this program was to define and solve key problems which are central to the evaluation and ultimate realization of various concepts for ship propulsion applications.

The results of this program are reported in detail in a series of progress reports, technical papers and MIT theses which are listed in Section XI of this report. As a guide to this large set of documents, critical abstracts have been prepared for all of the papers and theses, and these are included in Section XII. The body of this report is a very brief summary of our results and conclusions.

The work performed under this contract consisted of a theoretical investigation of several types of alternating current superconducting machinery for ship propulsion, an evaluation of refrigeration requirements for AC superconducting machines, and an experimental program concerned with two separate AC machine concepts.

The principal contributors to this research program were:

Bejan, Adrian - Research Associate, Mechanical Engineering

January 1, 1975 to May 31, 1976 - Cryogenic refrigeration
of ac superconducting machines.

Cabazon, Luis I. G. - Research Assistant, Mechanical Engineering

June, 1973 to July, 1974 - First experiment on thyristor
switched ac motor.

Denizmen, Kutsal A. - Lt. j.g., Turkish Navy

Student, Naval Postgraduate Program, September, 1972 to May, 1973.
Design study of high-speed ac generator.

Donahoe, J. Frederick - Research Assistant, Electrical Engineering

September, 1975 to December 31, 1976

Final experiment on thyristor switched ac motor.

Keim, Thomas A. - Staff Engineer, Electrical Engineering
 June 27, 1972 to June, 1976.
 General contributions, support and coordination of program.

Kirtley, J. L., Jr. - Assistant Professor, Electrical Engineering
 January 27, 1972 to December 31, 1976
 Research supervisor.

Minervini, Joseph Vito - Research Assistant, Mechanical Engineering
 September 1, 1972 to January, 1974
 Analysis of multipole, low speed motor.

Redding, John A. - Research Assistant, Electrical Engineering
 September 1, 1974 to Aug. 31, 1975
 Second experiment with thyristor switched AC motor.

Reynerson, Donald M. - Lt., U. S. Navy
 Student, Naval Postgraduate Program - May 29, 1974 to May 31, 1975
 Analysis of torque compensated motor.

Rumore, Frank C. - Research Assistant, Mechanical Engineering
 Feb. 1, 1975 to August, 1976
 Final analysis of rotating air-gap armature machines.

Smith, J. L., Jr. - Professor, Mechanical Engineering
 June 27, 1972 to December 31, 1976
 Research Supervisor

Solan, John Michael - Lt., U. S. Navy
 Student, Naval Postgraduate Program - September, 1972 to June, 1973
 Analysis of torque compensated motors.

Stetkar, J. W. - Research Assistant, Nuclear Engineering
 June 1, 1973 to August, 1974
 Experiment on rotating air-gap armature

Thullen, P. - Associate Professor, Mechanical Engineering
 June 27, 1972 to June 30, 1976
 Research supervision

II. Background

The advent of high-field stabilized superconductors and marine gas turbines has motivated a re-examination of electric drives for ship propulsion during the last several years. In addition, a number of advanced ship concepts have propulsion requirements not easily met with conventional ship drive systems. Superconduction electrical machinery promises equipment which is light and small, thereby overcoming one of the major disadvantages of electric drives with conventional machinery.

Direct-current drives traditionally are desirable because the system provides rapid and continuous control of the ship's propellers for good maneuverability and high efficiency. Thus superconductors were first applied to dc machines of the homopolar configuration. The superconducting homopolar machine can increase the maximum practical power level for dc drives while allowing small lightweight design. In addition, the cryogenic problems are minimized since the superconducting field winding is not influenced by the armature reaction field, and thus has no mechanical reaction forces. However, the homopolar configuration requires that the full electric power of the machine must be carried onto the rotor at high current and low voltage which presents significant current collection problems in high-power machines.

Traditionally, high-power electric machines have been ac machines since the electrical terminals are directly connected to stationary armature windings. Thus a high-power superconducting ac machine will logically require a rotating superconducting field winding. In 1967 the MIT Cryogenic Engineering Laboratory and the MIT Electric Power Systems Engineering Laboratory joined forces to prove that high-power ac synchronous machines with rotating superconducting field windings were practical.

By June 1969 the concept was demonstrated in a small experimental machine. Since then a 3-MVA experiment has been developed by the group at MIT, and a 5-MVA machine has been constructed at the Westinghouse Research Laboratories. These experimental programs and the associated analytical efforts have shown a high potential for the application of superconducting synchronous generators in large electric power stations.

Once the rotating superconducting-field machine had been demonstrated

and its potentials explored for one application, it became apparent that a wide range of possibilities were open for the application of superconductors to ship drives. The group at MIT undertook preliminary studies of a number of these rotating field ac machine systems through unsponsored thesis projects. As a result of these studies and as a natural result of the program on large synchronous machines for the Electric Power Research Institute, several concepts were evolved which appeared to warrant more detailed studies.

This background formed the basis for the original proposal for this contract.

The work under this contract has been related to two inventions which have been patented. Patent 3,742,265, "Superconducting Apparatus with Double Armature Structure", is related to the work done on rotating air-gap armature machines. This invention as defined by the claims was conceived prior to the contract. The work done under the contract did not constitute reduction of the invention to practice as that term is used in patent law. However, some of the work was definitely related to the patent.

Patent 3,909,684, "AC Powered Thyristor Switched Electric Motors Having Superconducting Fields", acknowledges the Office of Naval Research as the sponsoring agency.

No other patentable inventions were made during the course of the work under the contract.

III. Investigations Performed

Several different types of machine were studied as part of this contract. All machines considered were of the class of alternating current machines. The types of machines considered were:

1. Multipole, low speed motors
2. Torque compensated motors
3. High speed generators
4. Rotating air-gap armature machines
5. Thyristor switched ac motors

The first three of these machine types received only theoretical attention. The last two types listed were the subject of experimental study. The rotating air-gap armature machine used as a superconducting induction motor received both experimental and theoretical attention.

In addition, a rather extensive theoretical study of the refrigeration requirements for ac superconducting electric machines was performed. The results of this study are applicable to a broad range of machines.

IV. Multipole, Low-Speed Motors

This class of machine has application in large drives with relatively low propeller speed and relatively high electrical frequency, such as would be the case in "synchronous-synchronous" systems with no frequency changing apparatus. The advantage of this type of system, of course, is simplicity. The disadvantages are size and weight of the motor, and control difficulties.

Early in the investigation, an attempt was made to design a low speed synchronous motor, to be coupled with a generator such as the example given in Section VI. The algorithms for computerized design of many-pole machines are more complicated than for two-pole machines, so trial designs were performed using engineering judgment rather than a mechanized procedure to select parameters. The initial attempts at this process led to designs of large, bulky machines of low power density. This result, later reinforced by the opinions of other researchers that large, high-pole-number, superconducting synchronous machines were either impractical without the extensive use of iron or generally unfeasible, motivated a search for a simple explanation of the limitations on power density in high-pole-number synchronous machines.

A two-dimensional magnetic field model in rectangular coordinates provides the desired explanation. Neglecting curvature, a machine with windings having radial thicknesses thin with respect to the air gap radius may be modelled in rectangular coordinates as a portion of an array of windings extending to infinity (Fig. IV-1). The field expressions for such an array are simple sums of exponentials, and are easy to interpret. Expressions for self and mutual reactances and for power output have been derived from the rectangular coordinate model.

A result from this simple model is that the critical parameter is the pole pitch, the distance between the geometric centers of two adjacent coil sides (ℓ in Fig. IV-2). For practical superconducting coils there is a maximum practical flux density, occurring at the coil midplane. The coupling between the field and armature is dependent on the air gap flux. For maximum coupling the air gap flux density should be the largest possible fraction of the superconductor-limited midplane flux density.

For any given flux density at the coil midplane ($y=0$ in Fig. IV-2), flux density within the winding volume falls off with distance from the

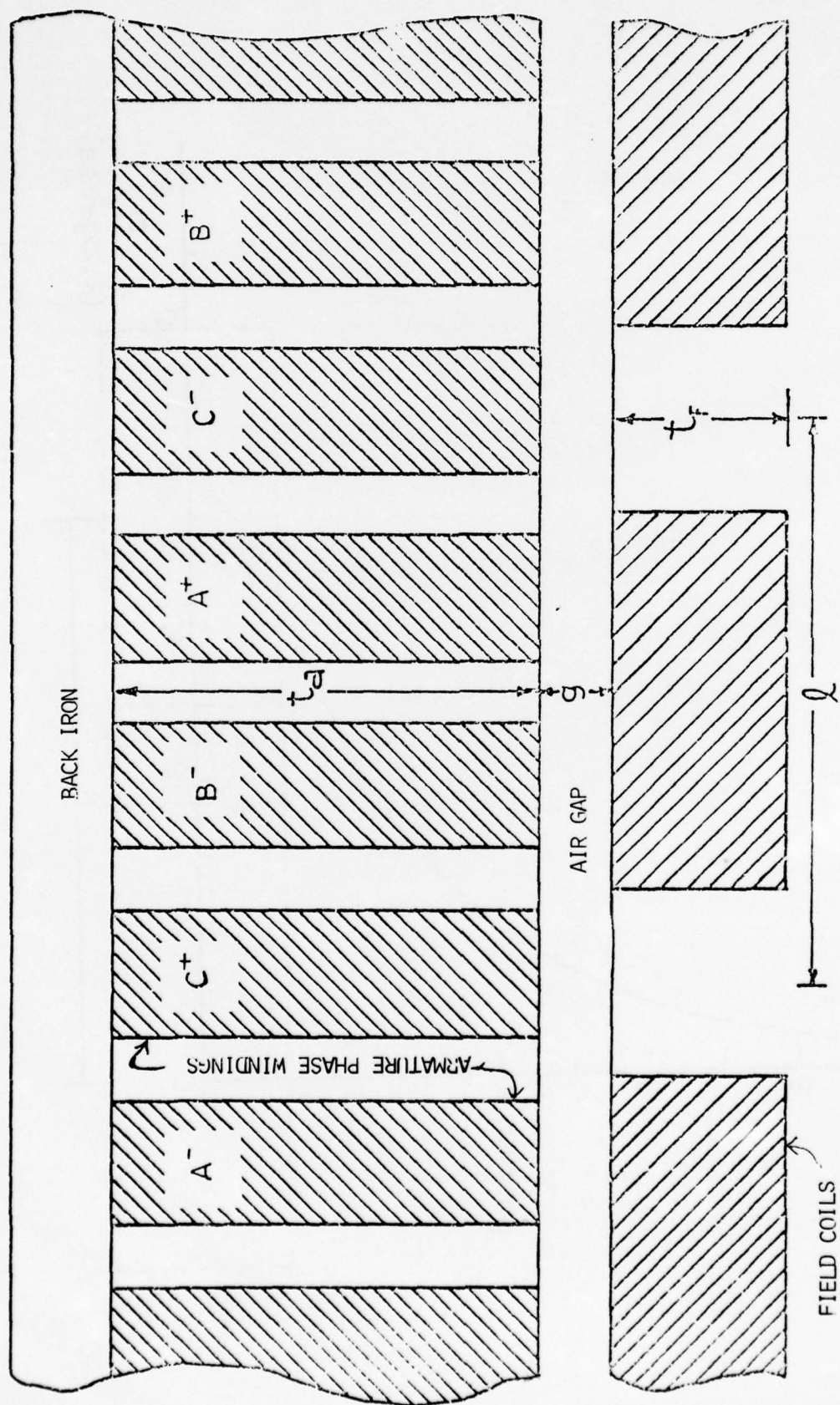


Fig. IV-1 Rectangular Coordinate Multipole Machine Model

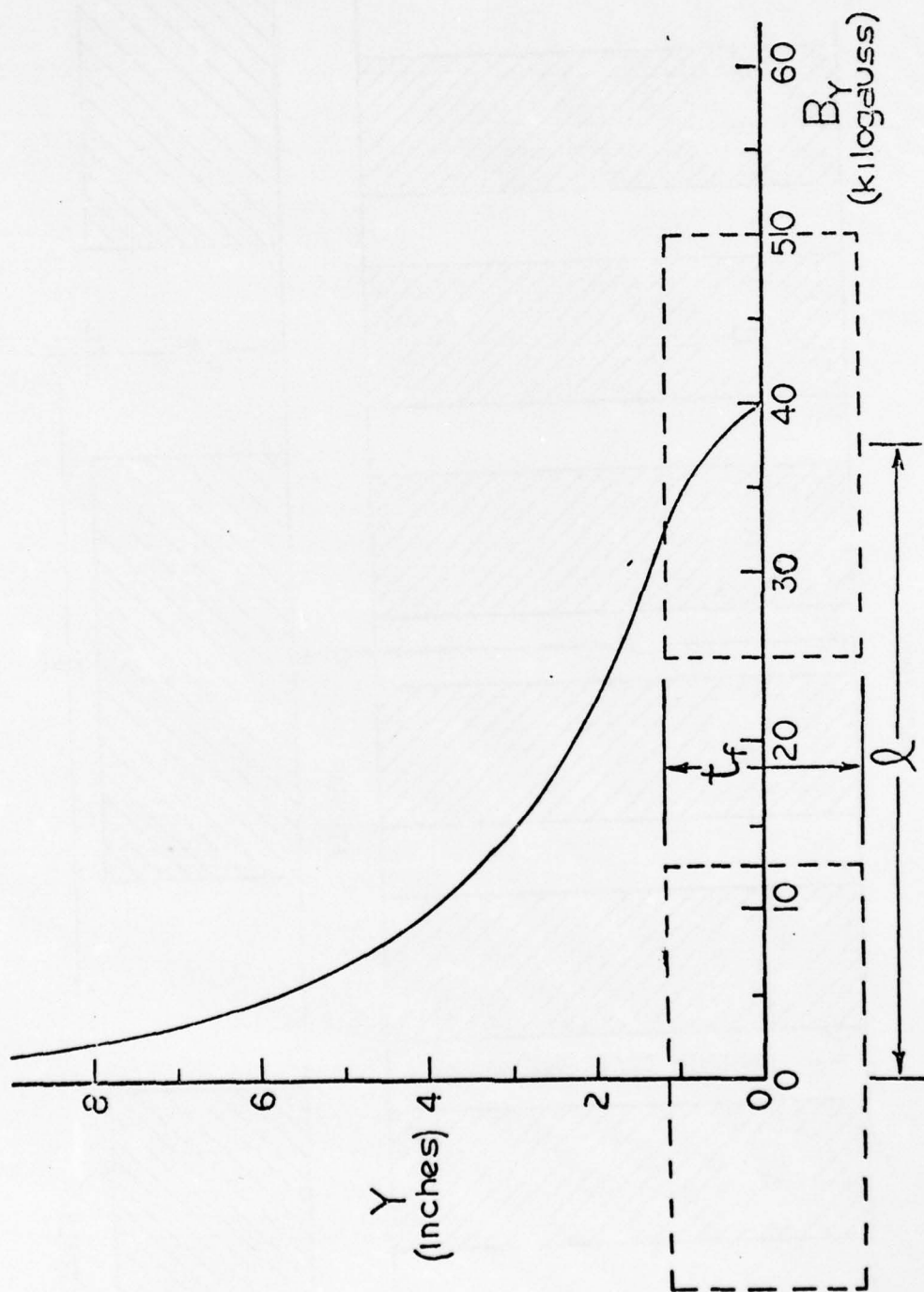


Fig. IV-2 Radial Flux Density vs. Distance from Field Winding Midplane

midplane as a function with a characteristic length proportional to the pole pitch. At the practical maximum flux density, there is a maximum current density at which the superconducting winding may be reliably operated without field quenching. The field winding thickness t_f required to obtain this maximum midplane flux density (operating the winding at the corresponding maximum current density) decreases as pole pitch increases. It is plausible from the shape of the B_y - y curve in Fig. IV-2 that the achievable flux density at the edge of the winding ($y=t/2$) and hence the achievable armature-to-field coupling, increases as pole pitch increases and winding thickness decreases. It can be shown mathematically that this is, indeed, the case.

The exact dependence of power density on pole pitch is shown for a specific case in Fig. IV-3. It should be noted that the volume on which this power density is based is the active volume of the machine; that is, the volume enclosed between field winding inner radius and armature outer radius, and not the total machine volume. Below a certain pole pitch (approximately $\ell = 6$ inches) the power density of a superconducting machine is not significantly greater than the power density of an iron-and-copper machine. Therefore, for superconducting multipole machines there exists a minimum practical pole pitch. Also, for a given electrical frequency and shaft speed, there is a minimum practical circumference (number of poles times pole pitch) and diameter, independent of power rating. Machines below a certain power level will be designed to this minimum diameter, and power output for these machines will depend on their lengths. At lower powers, as these minimum diameter machines grow short compared to a pole pitch, axial fringing of the field causes an increasing loss of field-to-armature coupling. The result is that machine rating decreases much more rapidly than machine volume, resulting in rapidly decreasing power density. Thus for a given electrical frequency and shaft speed, there is a practical minimum output power rating for a multipole superconducting machine. An example design to be presented later will show that for one case at least, this minimum power level is low enough to permit ship propulsion applications.

An immediate outgrowth of the simplicity of the rectangular coordinate analysis is insight into design rules for multipole superconducting machines. For example, it is easy to show that there is a maximum practical armature thickness for any pole pitch. Beyond a certain armature thickness,

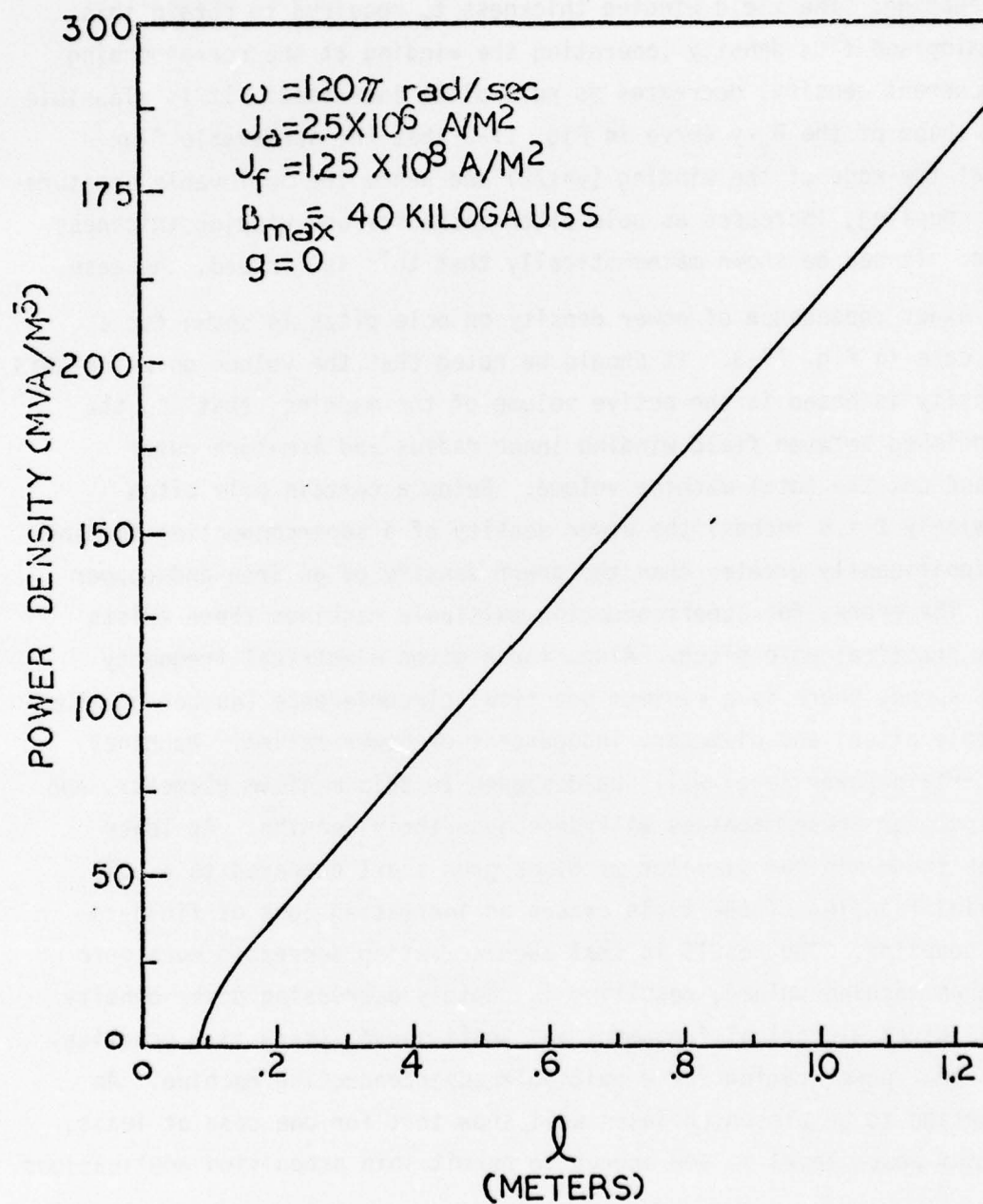


Fig. IV-3 Power Density vs. Pole Pitch

machine output ceases to increase with thickness (see Fig. IV-4), but armature reactance, loss, and cost do continue to increase.

Because of its simplicity and utility, the rectangular coordinate analysis has been developed to the point where it is possible to do a complete preliminary electromagnetic design of a multipole machine without reference to the slightly more accurate cylindrical-coordinate analysis. Thus the simple analysis can be used to numerically evaluate the minimum practical power for superconducting multipole machines and to reduce the number of iterations in the design of these machines.

Figure IV-5 shows a 40,000 HP 60 cycle 120 RPM superconducting motor designed by such a technique, next to an iron-and-copper machine of similar rating, frequency, and speed. Table IV-1 gives details of the superconducting machine design. (40,000 HP is not the minimum practical power for this frequency ratio; the rating was determined because of the availability of data for the conventional machine intended for installation in a large tanker.) The superconducting machine has a diameter little more than half that of the conventional machine. Thus for this case a fixed ratio speed reduction between prime mover and propeller may be effectively accomplished in superconducting a.c. drives by use of appropriate motor pole number.

The major cryogenic problem of large low-speed motors is to transmit rotor torque from the field winding to the shaft without excessive heat leak. A general solution to this problem has been performed by Smith and Bejan and is reported in Section IX. Applied to this case, the results indicate that the heat leak may be made acceptably low. A .019 inch thick, full field winding diameter stainless steel tube will transmit the full shaft torque at a stress of 35,000 psi. If the tube is made ten inches long and cooled with a single stream of helium, the theoretical minimum flow rate is 3.1 liters/hour, using the results of Ref. (11). Such a tube will buckle before it fails in shear, but buckling resistance may be improved without excessive heat leak by the addition of circumferential stiffening rings.

A detailed discussion of the rectangular-coordinate field analysis and a sample low-speed motor design resulting from the analysis have been reported in a thesis by Minervini ⁽⁵⁾, and in a paper by Minervini, Keim, and Thullen ⁽⁸⁾.

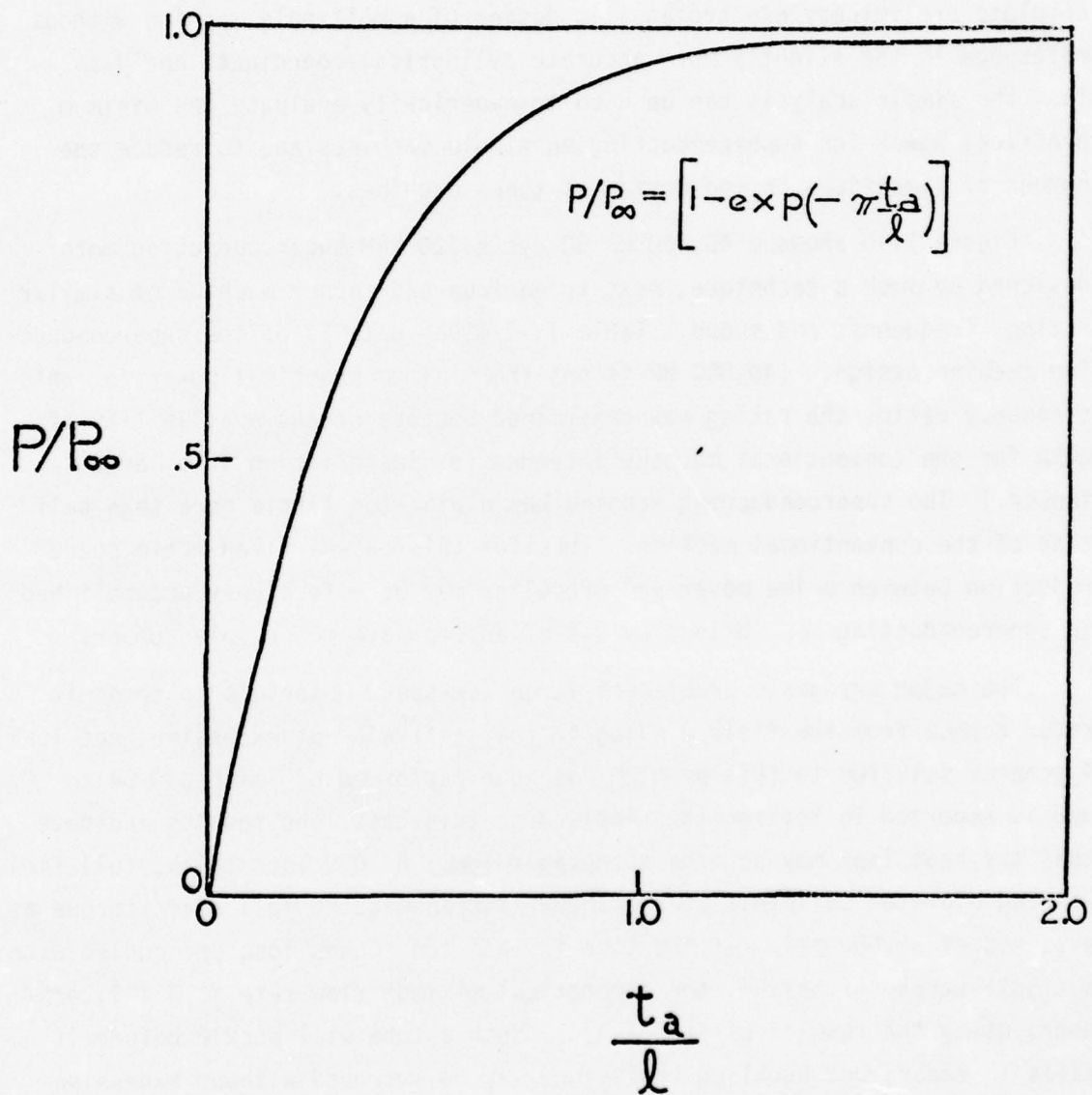


Fig. IV-4 Power Output vs. Armature Thickness

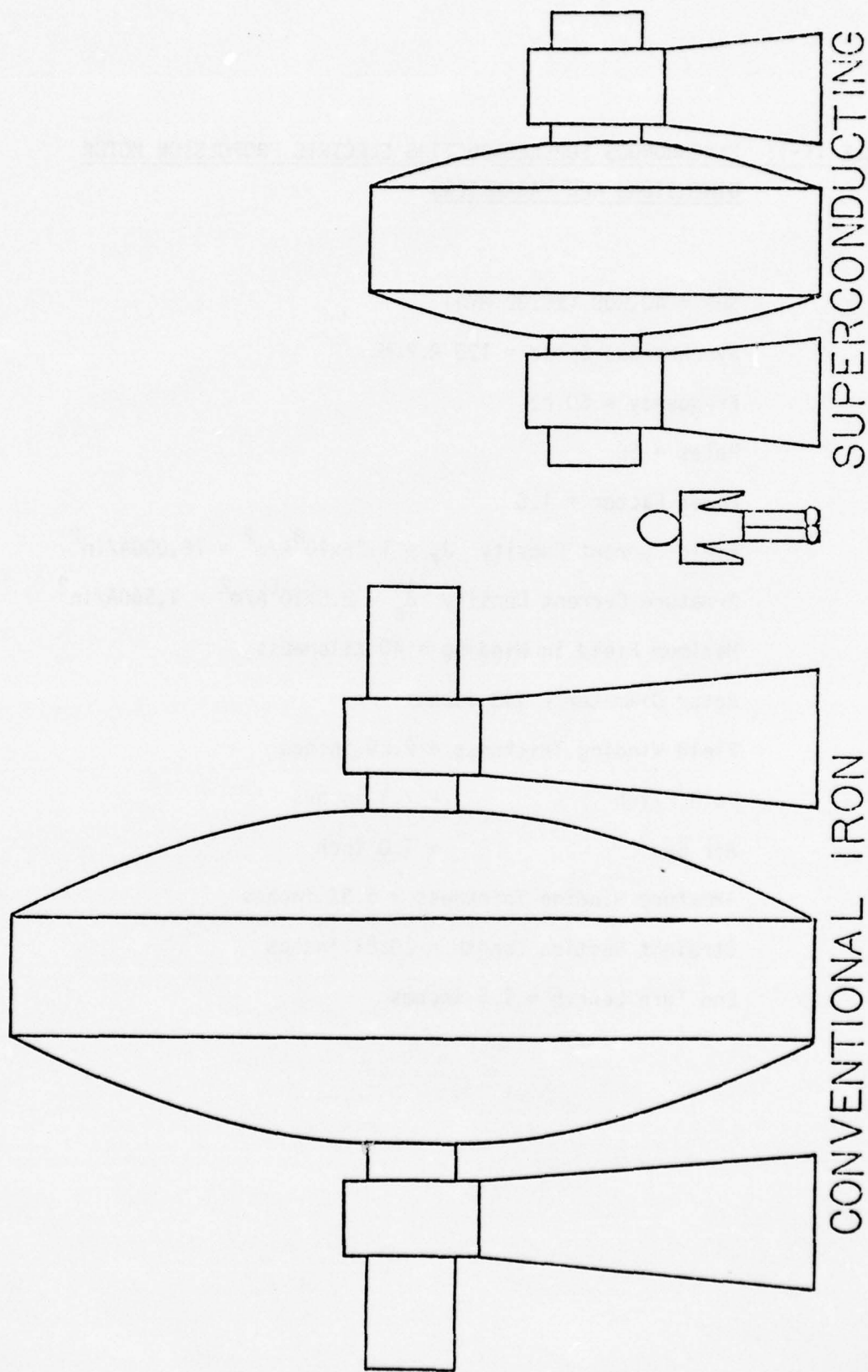


Fig. IV-5 Comparison of Conventional and Superconducting 40,000 hp Low-Speed Motors

TABLE IV-1: SYNCHRONOUS SUPERCONDUCTING ELECTRIC PROPULSION MOTOR
DIMENSIONS AND PARAMETERS

SHP = 40,000 (29.82 MVA)

Synchronous Speed = 120 R.P.M.

Frequency = 60 hz

Poles = 60

Power Factor = 1.0

Field Current Density $J_f = 1.25 \times 10^8 \text{ A/m}^2 = 78,000 \text{ A/in}^2$

Armature Current Density $J_a = 2.5 \times 10^6 \text{ A/m}^2 = 1,560 \text{ A/in}^2$

Maximum Field in Winding = 40 Kilogauss

Rotor Diameter = 143 inches

Field Winding Thickness = 2.29 inches

Pole Pitch = 7.5 inches

Air Gap = 1.0 inch

Armature Winding Thickness = 5.52 inches

Straight Section Length = 20.81 inches

End Turn Length = 7.5 inches

V. Torque-Compensated Rotating-Armature Machines

A more recent concept for an ac superconducting propulsion motor is essentially an inside-out synchronous machine with a compensating winding to remove the reaction torque from the superconducting field winding. This concept was first proposed in October 1973. Analysis and evaluation was carried out, and steady-state analysis was completed in May 1975. The graduate student who carried out this phase of the study is a U.S. Navy officer in the U.S. Navy postgraduate program at MIT.

The motor will have a stationary superconducting field winding and a room-temperature rotating armature winding. The armature is to be the central member. The field winding will be surrounded by a solid, room-temperature iron flux return path, positioned as close as possible to the field winding and operating in a magnetically saturated condition. A third winding (direct current) operating at room-temperature and positioned on the quadrature axis may be provided to assume the load torque through a room-temperature structure, thus freeing the field support structure of this duty. Power will be supplied to the armature through slip rings.

This particular design should have the following attributes:

1. It may be feasible to develop a small volume cylindrical drive motor for use with submerged drive pods and high-speed propellers.
2. The iron flux return path may serve as the outer vessel.
3. A stationary field winding permits solid electrical and coolant connections.
4. There is no need for solid-state switchgear in the drive motor pod.
5. Slip ring current requirements are equivalent to those of double-armature design, although the slip rings may have to handle substantially higher power levels.
6. High operating efficiency is achieved at synchronous speeds.
7. A stationary induction-type starting winding may be necessary. This may be either an actual winding or a damper shell.
8. Net torque on the field winding may be eliminated.

Power can be supplied to the motor either by a gas-turbine synchronous generator (normal or superconducting), which will provide limited speed control; or by a constant-speed alternator with solid-state frequency changer

which can provide greater speed control. Regardless of the method employed for speed control, shaft direction can be controlled by reversing the field current, employing a CRPP, or switching armature phases.

Analysis carried out by Reynerson has culminated in a thesis ⁽¹⁰⁾ which presents a steady-state magnetic field analysis, a study of various machine configurations (geometries), and a trial design for a 22,700 hp motor.

Magnetic field analysis of this machine is similar to that derived for previously analyzed superconducting generators in that it is two dimensional and assumes no iron within the bore of the rotor. It differs by considering three active windings with a rotating armature as the central member, and includes the effects of finite permeability of the outer iron shield. Machine inductance, power, and torque expressions are derived based on the two-dimensional field distributions and are utilized in trial designs.

Four-pole motors of various configuration were investigated to determine the best spatial relationships between the component parts. The configurations studied can be lumped into the following classes: 1) machines with the compensating winding between the field and armature windings; or 2) machines with the field winding between the compensating and armature windings; and 3) machines with gimbal-mounted field windings and fixed compensator currents; or 4) machines with fixed field windings and variable compensator currents. It was concluded that a fixed field winding located between the armature and compensator windings would produce a motor with the highest power density.

A trial design for a motor was produced with specifications as listed in Table V-1. Further information may be obtained from Reynerson's thesis.

TABLE V-1: DATA FOR A FEASIBLE TORQUE-COMPENSATED MACHINE

<u>Parameter</u>	<u>Value</u>
Design Horsepower	22,700 shp
Power Factor	0.85
kVA Rating	19,900 kVA
Design Speed	1800 rpm
Number of poles	4
Rated Compensator Current Density, J_c	1.4×10^6 Amps/m ²
Rated Field Current Density, J_f	$4. \times 10^7$ Amps/m ²
Rated Armature Current Density, J_a	2.25×10^6 Amps/m ²
Rated Terminal Phase Voltage	6300 volts rms
Rated Terminal Line Voltage, V_T	10,000 volts rms
Phase Angle between Main and Compensator Fields, α	45°
Armature Winding Angle, θ_{wa}	28°
Field Winding Angle, θ_{wf}	80°
Compensator Winding Angle, θ_{wc}	80°
Armature Space Factor, λ	.27
Armature Winding Inside Radius, R_{ai}	7."
Armature Winding Outside Radius, R_{ao}	11.5"
Field Winding Inside Radius, R_{fi}	12."
Field Winding Outside Radius, R_{fo}	13."
Compensator Winding Inside Radius, R_{ci}	13.5"
Compensator Winding Outside Radius, R_{co}	15.5"
Shield Inside Radius, R_{si}	16."
Shield Outside Radius, R_{so}	18"
Shield Permeability, μ_s	.009 Hy/in

TABLE V-1: Continued

<u>Parameter</u>	<u>Value</u>
Total Machine Length, ℓ_t	72"
Straight Section Length, ℓ	35"
Synchronous Reactance (per unit), x_d	0.12
Armature Conductivity	$\sigma = 6 \times 10^7$ mho/m
End Turn Length ($R_{ai} + R_{ao}$)	18."
Effective Lengths For:	
Self Inductance, Armature	53"
Self Inductance, Field	35"
Self Inductance, Compensator	35"
Mutual Inductance, Field-to-Armature	35"
Mutual Inductance, Compensator-to-Armature	35"
Conductor Loss	72"
Eddy-Current Loss	35"
Losses at Rated Conditions:	
Conduction (compensator and armature)	200hp
Eddy-currents	15hp
Total, percent of rating	.94%

VI. High-Speed Generators

Any electric drive system requires a prime mover connected to a generator. This section is concerned with the generator. It is expected that this machine will resemble equipment built for stationary application (turbine generators) more strongly than the motors it drives.

The generator is expected to couple to a high speed prime mover shaft (for example, that of a gas turbine), and will most likely be of two-pole design.

A design procedure for determining the critical dimensions of the electromagnetic shield of a two-pole superconducting generator has been developed. This procedure, while it is not a complete optimization routine, is a part of one.

The design of the electromagnetic shield is complicated by the conflicting requirements imposed on the shield. In the first place, the shield must intercept all transient torques and magnetic fields, to protect the cryogenic rotor. Because of this, the electromagnetic shield is subject to some very large torque and crushing loads during certain transients (such as electrical faults). At the same time, it is important to keep the shield as thin as possible, in order to maintain a high degree of coupling between the field winding and armature. This high degree of coupling is essential to maintain a high energy-conversion density.

The design procedure was developed by Denizmen (1).

The starting point was the basic relations for superconducting synchronous alternators which have been developed at MIT during the last few years. The elements of the design procedure are:

1. Geometric, maximum field, and maximum current density constraints are assumed for the machine.
2. The basic relations from the two-dimensional field analysis are used to establish the rating of the machine and to establish the level of fault forces on the shield
3. A three-dimensional stress analysis (using the thin shell approximation) is then used to determine the maximum stresses in the structural shell of the shield

4. If the shell is not strong enough to survive the fault, the geometry is changed--either by increasing field-to-armature spacing, or by making the shell thicker, or both. The analysis is then repeated with the new geometry. Iteration is continued until a shield of adequate strength is obtained.

This procedure was carried out for the design of a 20,000 horsepower, two-pole, 3600 RPM synchronous alternator. It was found that a shield which fills the air gap produced the best design (at least in this size machine). It was also found that the machine was best (most compact) when the shield consisted of a thin, highly conducting shell on the inner radius of a non-conducting support shell which filled the rest of the air gap. However, a machine with the shield constructed with the conducting shell on the outer radius of the non-conducting support shell was quite acceptable.

Figure VI-1 and Tables VI-1 and VI-2 show the savings achievable in weight and volume by use of the superconducting alternator. The tables give a reasonably detailed description of the design of the 20,000 HP superconducting machine.

A gas cooled torque tube has been designed for the 20,000 horsepower machine to demonstrate that rotating field machines can operate with reasonable liquid helium consumption. The torque of the machine can be carried by a tube 10 inches in diameter with a wall thickness of 0.044 inches, provided circumferential ribs are included to prevent buckling. The analysis ⁽¹¹⁾ applied to this torque tube shows that a 20-inch-long tube, continuously cooled by a single stream of helium, achieves optimum cooling with a flow of only 3.6 liters of liquid helium per hour. As with any superconducting winding additional cooling will be required for the transverse supports, for thermal radiation and for the current leads.

In conclusion the 20,000 HP superconducting generator is smaller and lighter than a similar conventional alternator. The space required to provide adequate mechanical strength for the rotor shield does not significantly compromise this size and weight advantage. The cryogenic refrigeration requirement for the rotor torque tube does not dominate the cooling requirement for the rotating field generator.

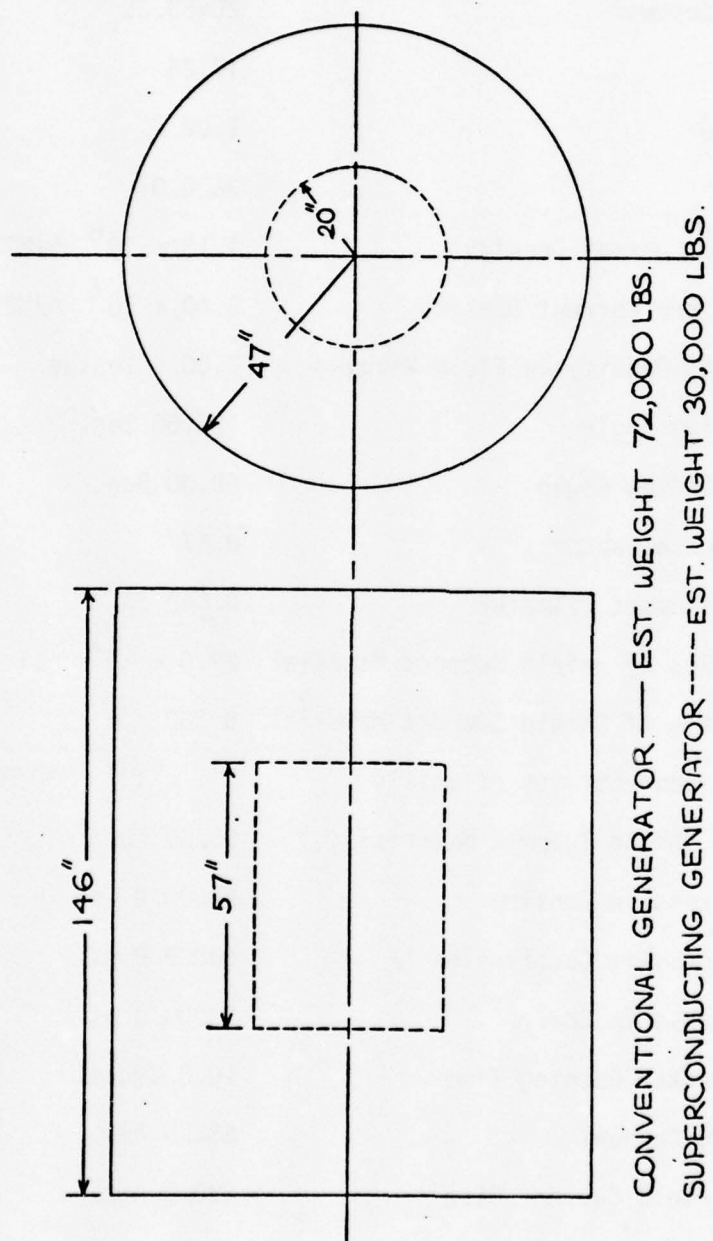


Figure VI-1
 Comparison Between 20,000 HP Conventional Generator
 and a Superconducting Generator

TABLE VI-1: DESIGN CONSTANTS

Design Horsepower	20450.25
MVA Rating	15.25
Power Factor	1.00
Design RPM	3600.0
Rated Field Current Density	1.15×10^8 A/M ²
Rated Armature Current Density	3.00×10^6 A/M ²
Maximum Flux Density in Field Winding	5.00 Teslas
Field Winding Angle	120.00 Deg.
Armature Winding Angle	60.00 Deg.
Armature Space Factor	0.27
Armature Filament Diameter	0.040 in.
Young Modulus of Shield Support Material	29.0×10^6 psi
Poisson Ratio of Shield Support Material	0.300
Electrical Conductivity of Shield	6.0×10^7 MHO/M
Density of Shield Support Material	0.290 lbs/in ³
Working Stress in Tension	50000.0 psi
Working Stress in Compression	50000.0 psi
Working Stress in Shear	30000.0 psi
Circuit Breaker Opening Time	10.0 Cycles
Rated Field Current	680.0 Amp.
Allowable Field Current Rise	420.0 Amp.

TABLE VI-2: MACHINE PARAMETERS

Field Winding Outside Radius	5.000 in.
Field Winding Inside Radius	2.760 in.
Armature Inside Radius	6.451 in.
Armature Outside Radius	9.354 in.
Shield Inside Radius	12.257 in.
Shield Outside Radius	19.887 in.
Total Length	58.848 in.
Straight Section Length	27.237 in.
Machine Volume	42.313 ft. ³
Weight of Active Parts	16418.903 lbs.
Primary Shield is Outside the Shield Structure Air Gap Length	1.4514 in.
Primary Shield Outside Radius	6.364 in.
Shield Structure Outside Radius	6.364 in.
Primary Shield Thickness	0.0 in.
Shield Structure Thickness	1.3410 in.
Shield Deflection Towards Field Winding Under Three Phase Fault	0.0220 in.
Shield Deflection Towards Armature Winding Under Three Phase Fault	0.0205 in.
Synchronous Reactance P.U.	0.2533
Transient Reactance P.U.	0.1875
Subtransient Reactance P.U.	0.1283
Machine Losses Percent of Machine Rating	0.751
Max. Radial Stress Under Three Phase Fault	3482.8 psi
Maximum Torque Under Line to Line Short Circuit From Load P.U.	10.303

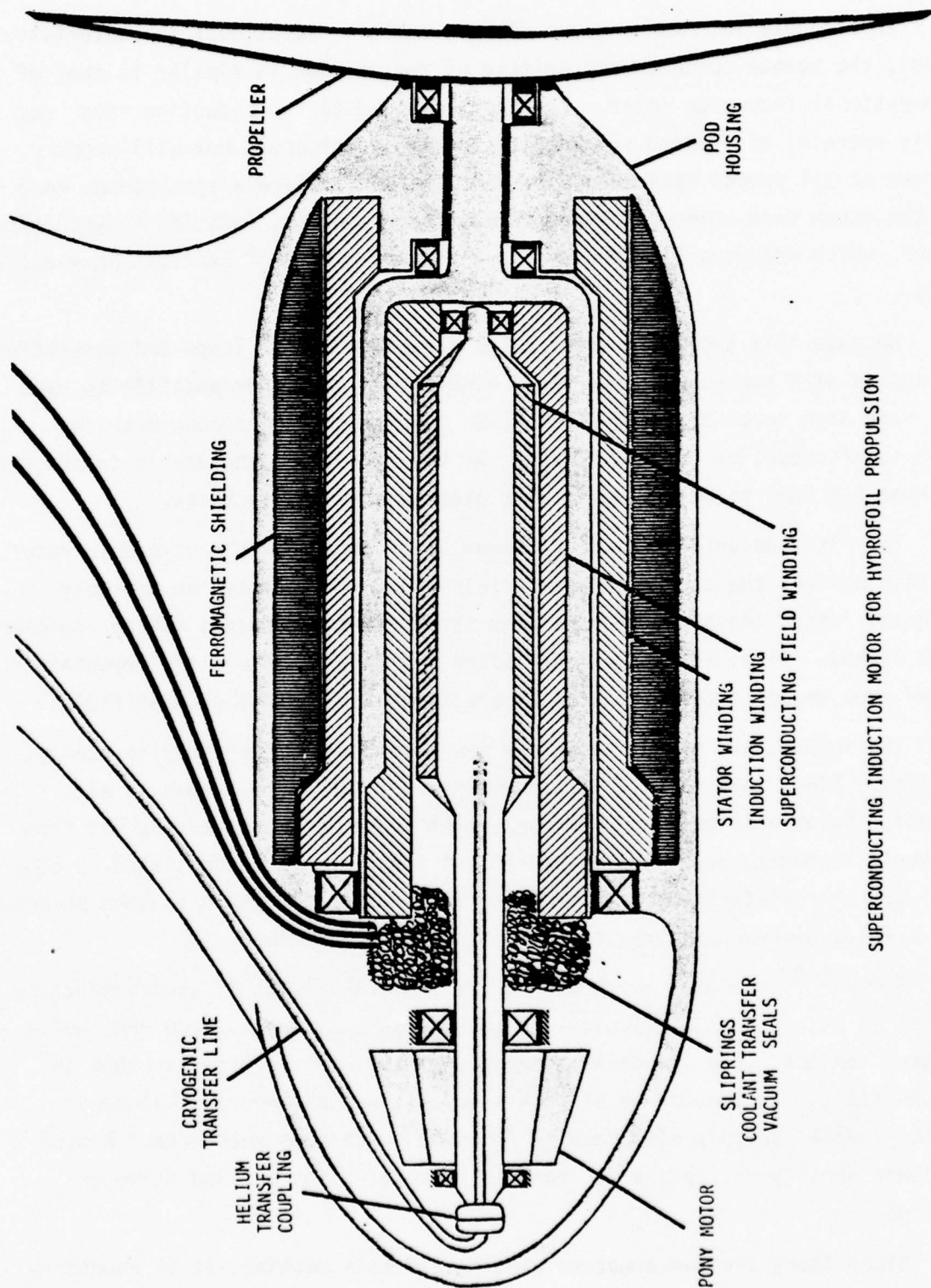
VII. Rotating Air-Gap Armature Machines

The superconducting induction motor is one of a class of machines called rotating air gap armature (RAGAM) machines. Machines of this class are expected to have very high power density with control characteristics superior to those of single rotor synchronous machines. The most likely application for machines of this class is synchronous-synchronous systems with relatively high speed propellers, where a large (more than 4:1) prime-mover to motor speed reduction is not required.

The basic configuration of a superconducting induction motor is shown in Fig. VII-1. The device has two concentric rotors. The inner rotor is cryogenic and contains the superconducting field winding. This rotor has no torque-carrying connections, and is freely spinning. The intermediate rotor carries an induction winding, similar to that on the rotor of a wound rotor induction motor. This winding is connected to an external control circuit, through slip rings. The external control circuit might merely be a resistor, or it could contain more complex power handling circuitry. This rotor is the torque-carrying element, and is connected directly to the shaft.

The outermost electrically active part of this machine is the armature, which is similar to a standard ac motor armature. It will probably be of the same form as an "air-gap" winding.

The interaction within this machine is a combination of two interactions. The superconducting field winding generates a large flux wave. Currents in the stationary armature interact with this flux wave to pull the inner rotor along at synchronous speed. The first interaction, then, is similar to that of a synchronous motor. The inner rotor, containing the superconducting field winding, is always running at synchronous speed, and the superconducting winding is in a constant dc field. The second interaction is between the induction winding and the main flux wave of the superconducting field winding. This interaction is similar to that of a conventional induction motor. If the induction rotor is rotating at a different speed from the main flux wave, a voltage is generated in its windings. This voltage in turn causes currents to flow in the windings of the induction rotor. These currents interact with the main flux wave to pull the induction rotor along with the main flux wave.



SUPERCONDUCTING INDUCTION MOTOR FOR HYDROFOIL PROPULSION

FIGURE VII-1

This double interaction gives rise to certain operational characteristics. First, the torque-speed characteristic of the machine is similar to that of a conventional induction motor. The shaft coupled to the induction rotor normally operates at a speed slightly less than synchronous, but will produce torque at all speeds less than synchronous speed, unlike a synchronous machine. On the other hand, these machines have a field winding, rotating at synchronous speed, which produces flux and provides the capability of controlling reactive power.

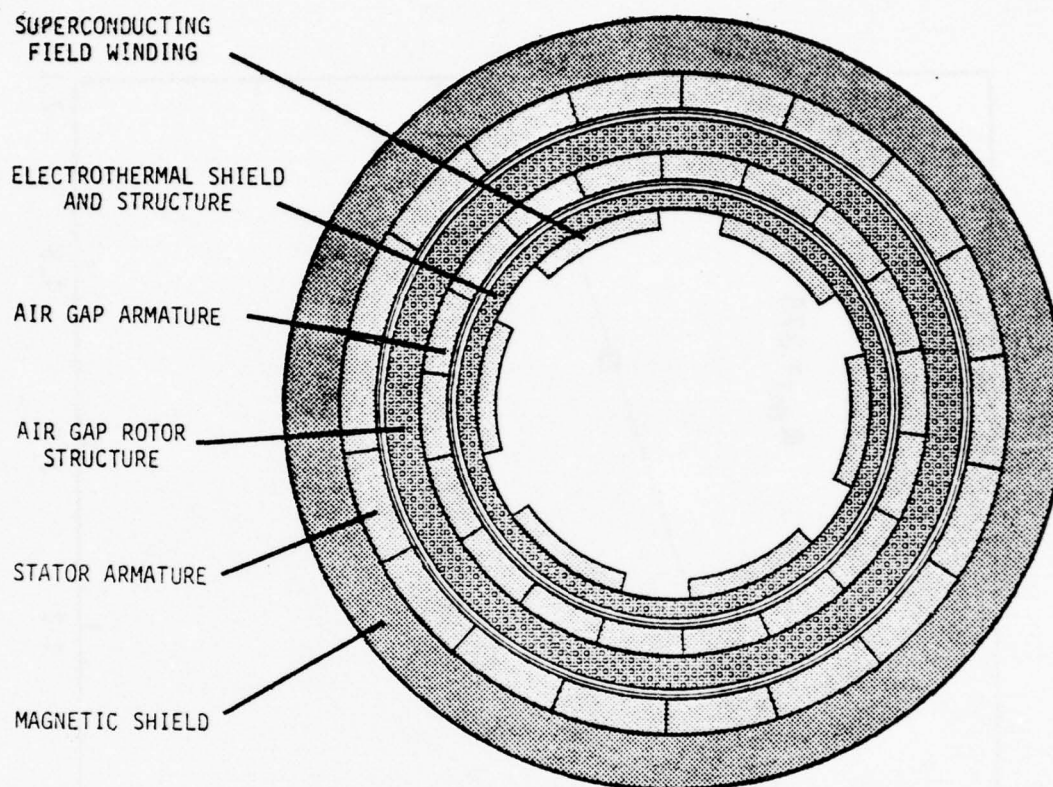
Because this type of machine takes advantage of the large mmf generating potential of a superconducting field winding, it should be possible to have the same high level of energy conversion density as synchronous machines with superconducting field windings. At the same time, the double-interaction machine has some potential advantages over synchronous machines.

The first advantage is the elimination of torque on the cryogenic rotor. In this design, the superconducting field winding is mounted on a freely spinning rotor, and thus does not need strong torque supports (which represent heat leaks). Also, the induction winding may help to shield the cryogenic rotor from magnetic forces caused by electrical transients such as faults.

The second, and major, advantage over synchronous machinery is controllability. Since this is an induction machine, it produces torque at all speeds. Because of this, a superconducting induction motor may be fed from a single frequency supply, with control of rotor torque accomplished by control of the resistance in the induction rotor circuit. There is then no need for complex high-power circuitry for changing frequencies.

Rumore⁽¹⁶⁾ has done a study of the electrical design of superconducting induction motors. In particular, he considered a six-pole, 1200 RPM configuration confined to a one meter outside diameter. One design is shown in Figure VII-2. In the course of this study, it was discovered that power density varies sharply with machine dimensions, as does reactance. A plot of power density vs. radius is shown in Fig. VII-3 for a fixed diameter machine.

Since there are two armature windings in this machine, it is necessary to coordinate the two windings to ensure that they are both operating at about the same fraction of their rating. If this is not done, one of the windings



Base Power - 11.1 MVA/METER

J_{copper} - 3.5×10^6 AMPS/METER²

J_{super} - 2.3×10^8 AMPS/METER²

X_d - .75

Full Load Slip - .0045

DIMENSIONS - METERS

RMO - .5

RMI - .426

RAO - .426

RAI - .383

RSO - .327

RSI - .289

RFO - .251

RFI - .226

SIX POLE SUPERCONDUCTING DUAL ROTOR INDUCTION MOTOR

FIGURE VII-2

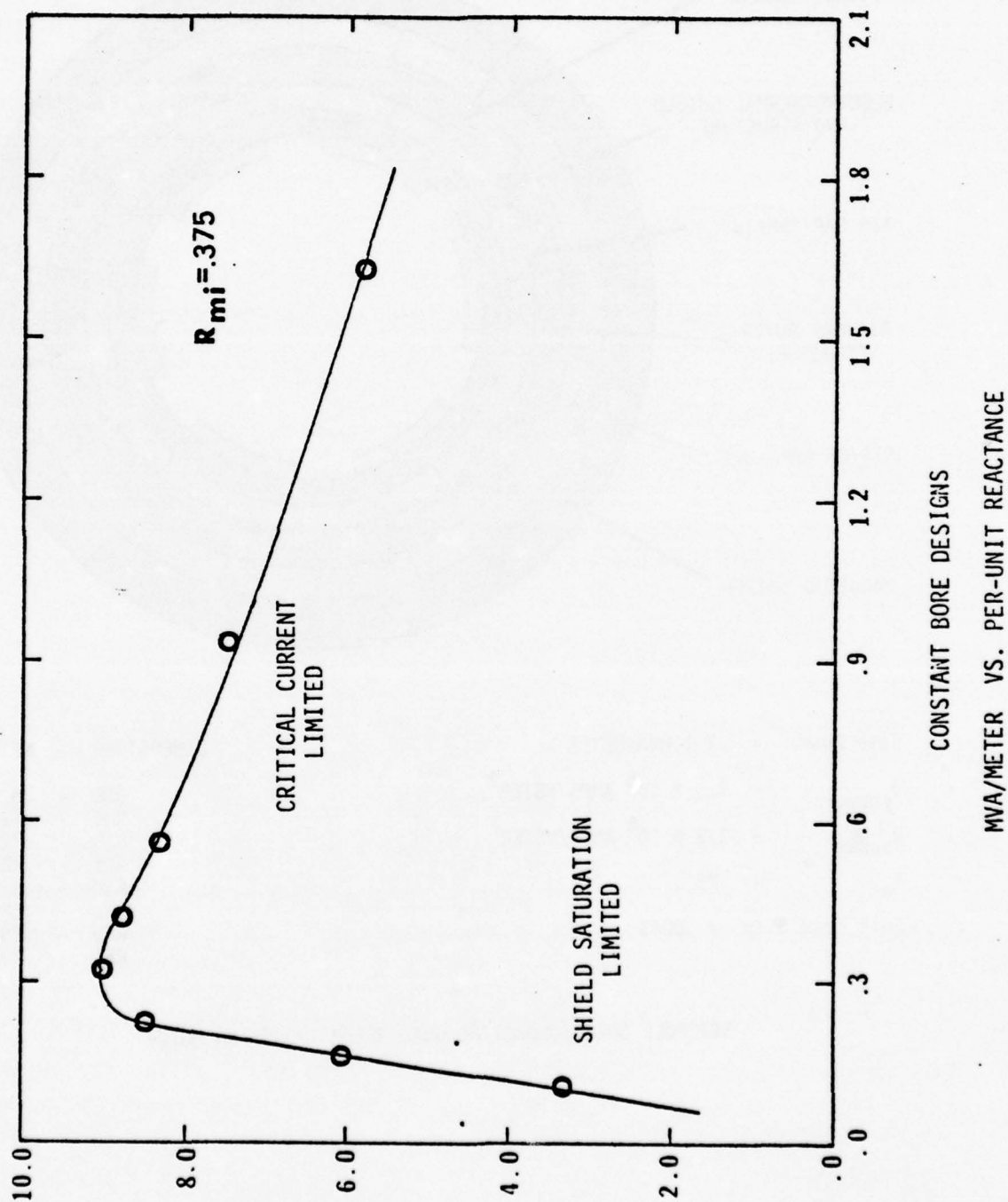


FIGURE VII-3

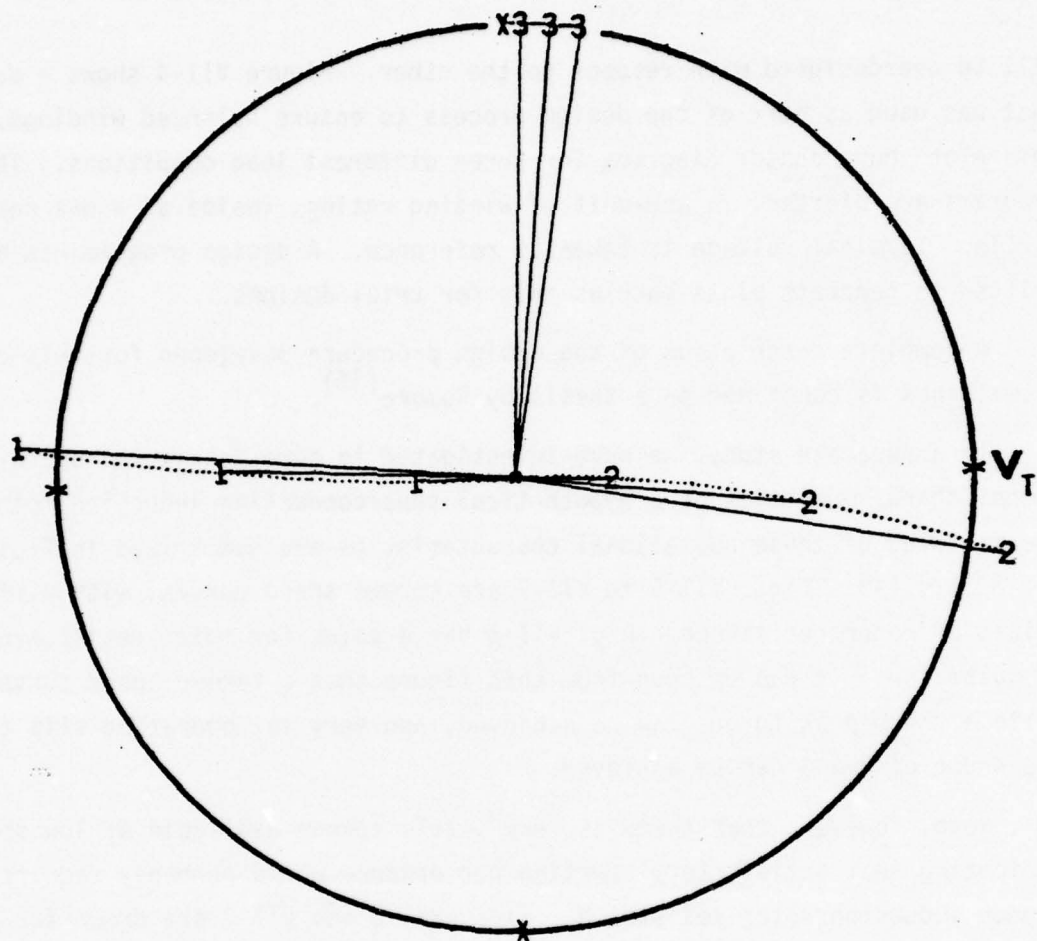
will be oversized with respect to the other. Figure VII-4 shows a device that was used as part of the design process to ensure balanced windings. This plot shows phasor diagrams for three different load conditions. These diagrams are plotted, in per-unit of winding rating, inside of a one per-unit circle. Terminal voltage is taken as reference. A design program has been written to generate plots such as this for trial designs.

A complete description of the design procedure developed for this class of machines is contained in a thesis by Rumore⁽¹⁶⁾.

In a separate study, we have investigated in some detail the operational characteristics of a hypothetical superconducting induction motor⁽⁴⁾. The features of these operational characteristics are summarized in Figs. VII-5 to VII-9. Figs. VII-5 to VII-7 are torque speed curves, with different values of rotor resistance. Fig. VII-5 has a value for rotor resistance that is quite low. It can be seen from this figure that a torque speed curve with quite a sharp peak torque can be achieved, and very low operating slip (on the order of 2-3%) can be achieved.

Note, however, that there is very little torque available at low speed, indicating that satisfactory starting performance would probably require higher induction rotor resistance. Figs. VII-6 and VII-7 are drawn for the same machine geometry, but with higher values of induction rotor circuit resistance. It can be seen from these figures that reasonable values of torque can be achieved at any speed by inserting the proper value of resistance into the rotor circuit. Fig. VII-8 shows the value of rotor resistance that will result in unit torque, as a function of shaft speed.

In Figs. VII-5 to VII-7, field current (E_f) has been included as a parameter. It can be seen that the value of current in the superconducting field winding can affect the torque-speed curve strongly. The value of field current also affects the power factor of the machine, as is shown in Fig. VII-9, which is a vee curve for this machine under conditions of rated torque at 5% slip. As can be seen from this curve, power factor can be made unity by picking the proper value of field current (and induction rotor circuit resistance). The proper value for field current is relatively low and does not depend strongly on speed or rotor circuit resistance. That is, the operating value for E_f will be somewhat smaller, on a per-unit basis,



This case depicts the steady state operation of the final design with a synchronous reactance of 0.75. Note the thermally balanced armatures and the excellent power factor regulation to full load.

- 1 = Armature #1 current
- 2 = Rotating armature current
- 3 = Field current

STEADY STATE PHASOR LOCI - E

Figure VII-4

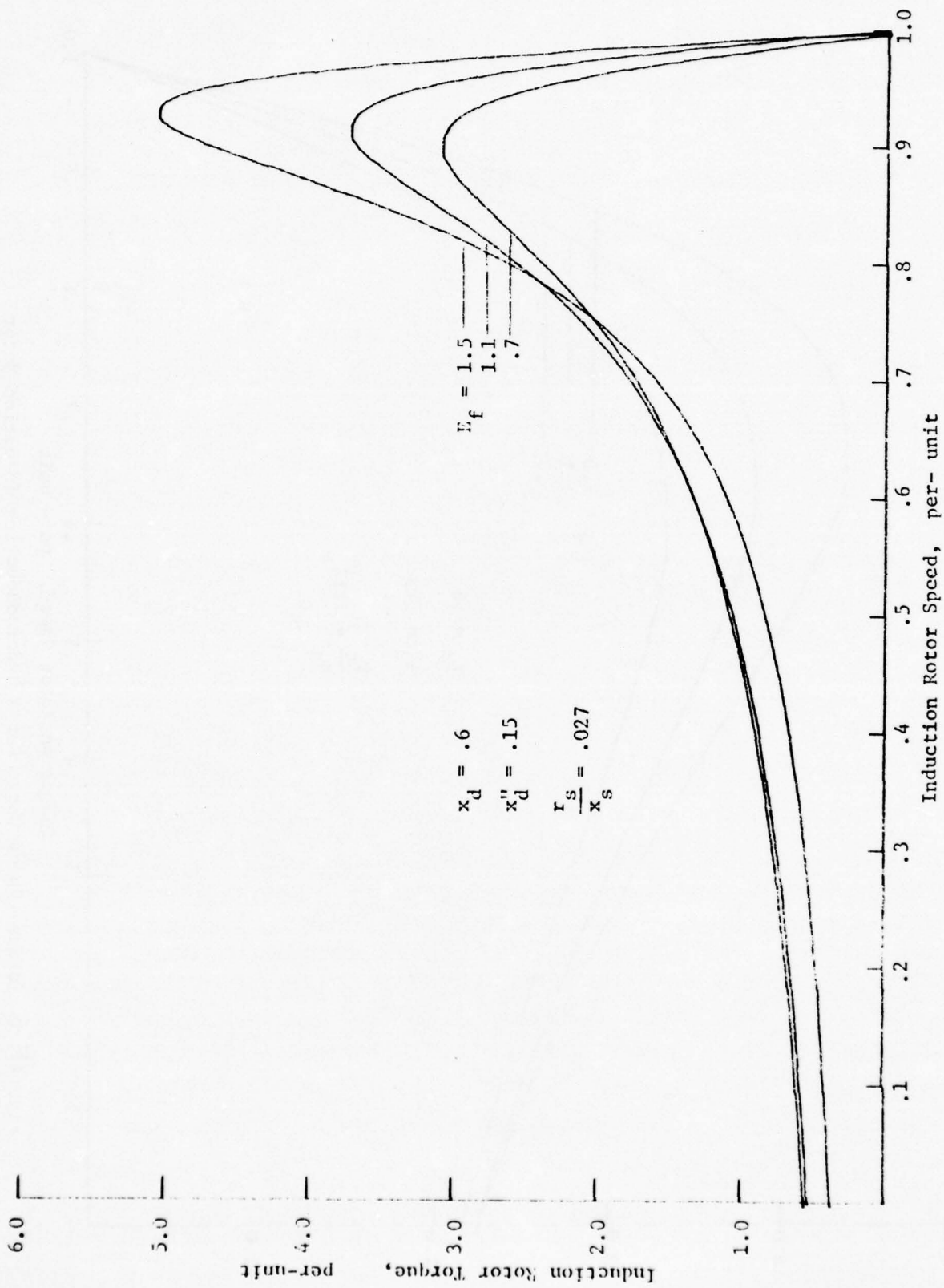


Fig. VII-5 Torque-Speed Curve For A Superconducting Induction Motor

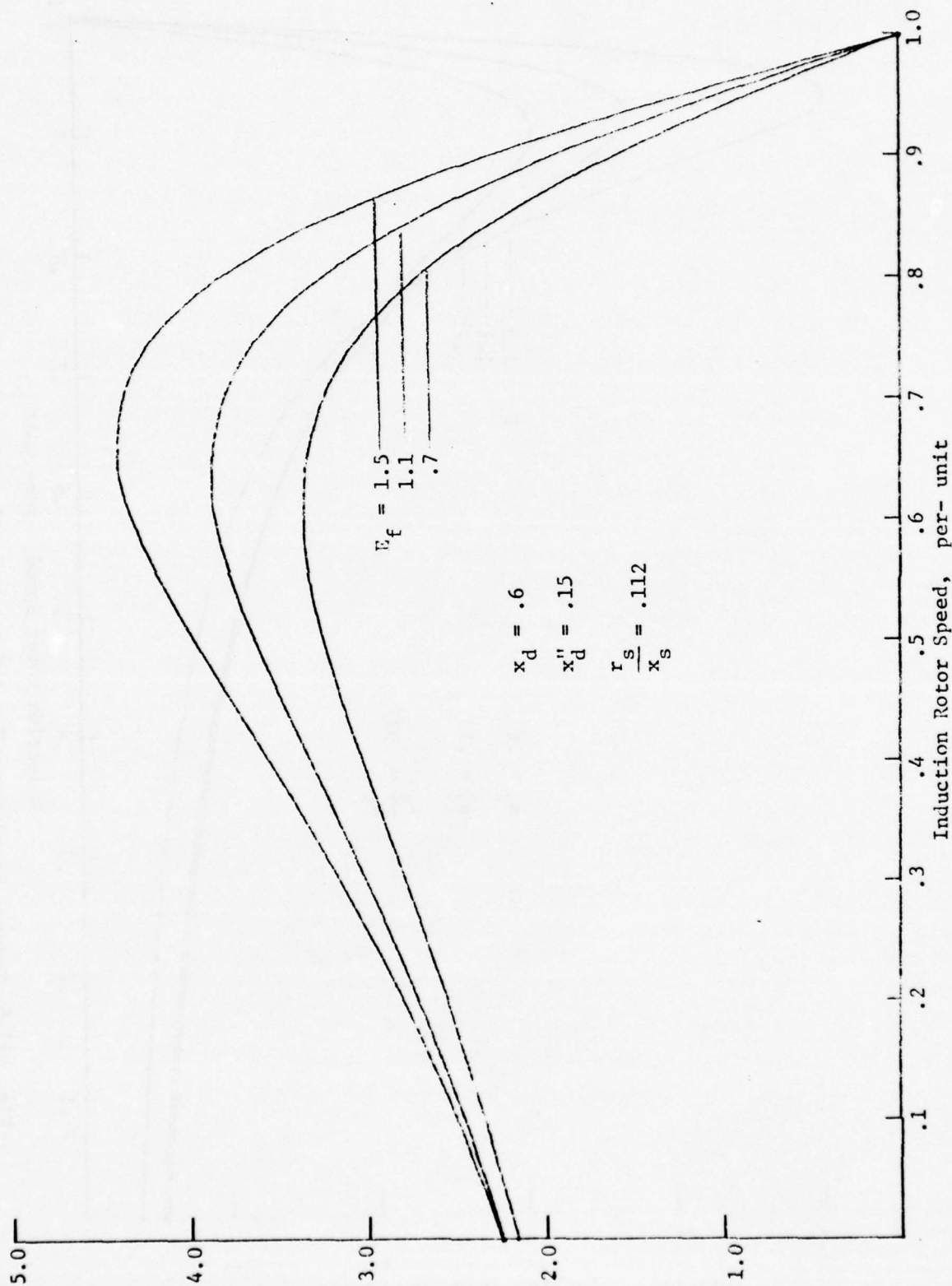


Fig. VII-6 Torque-Speed Curve For A Superconducting Induction Motor

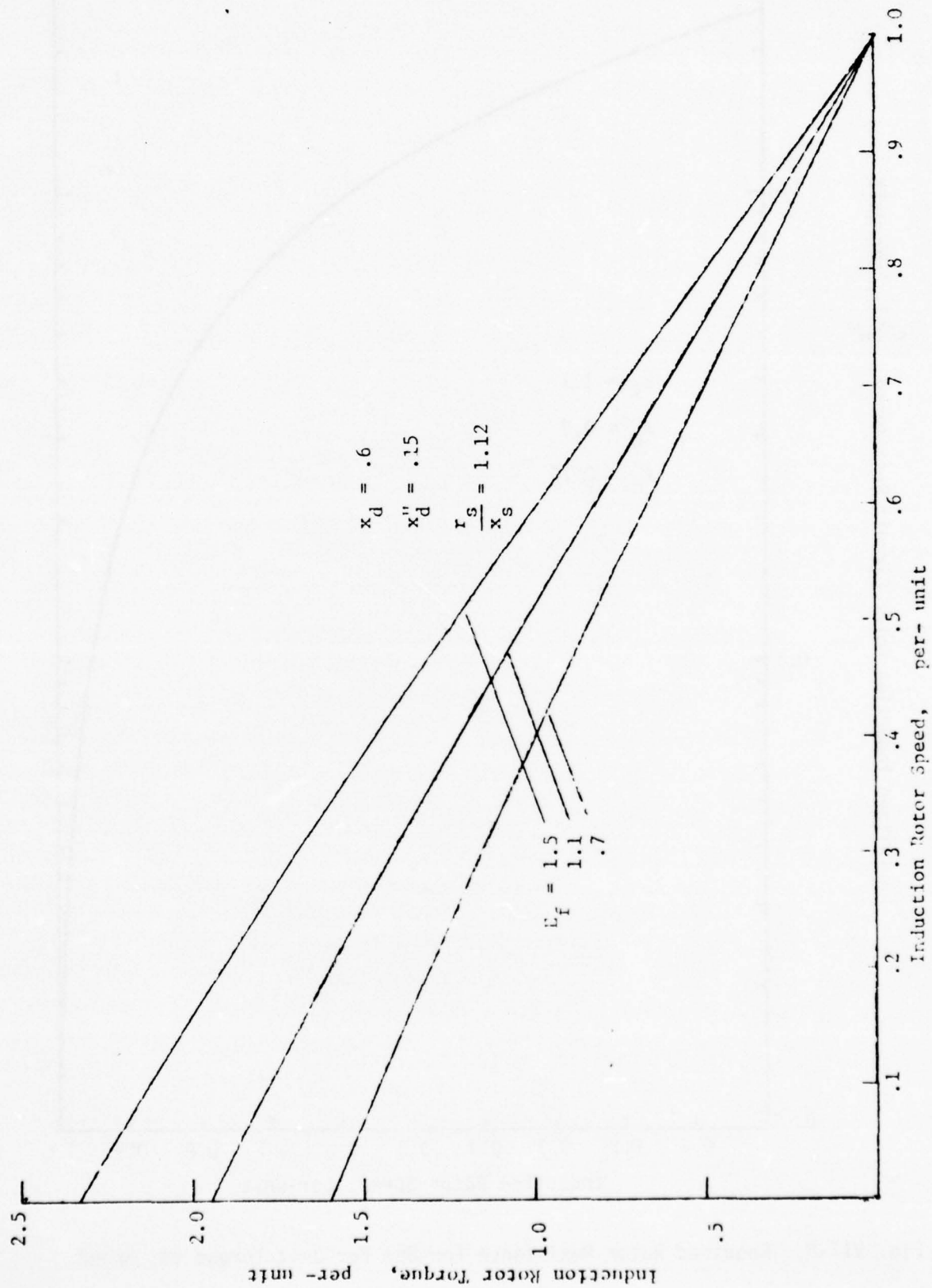


Fig. VII-7 Torque-Speed Curve for A Superconducting Induction Motor

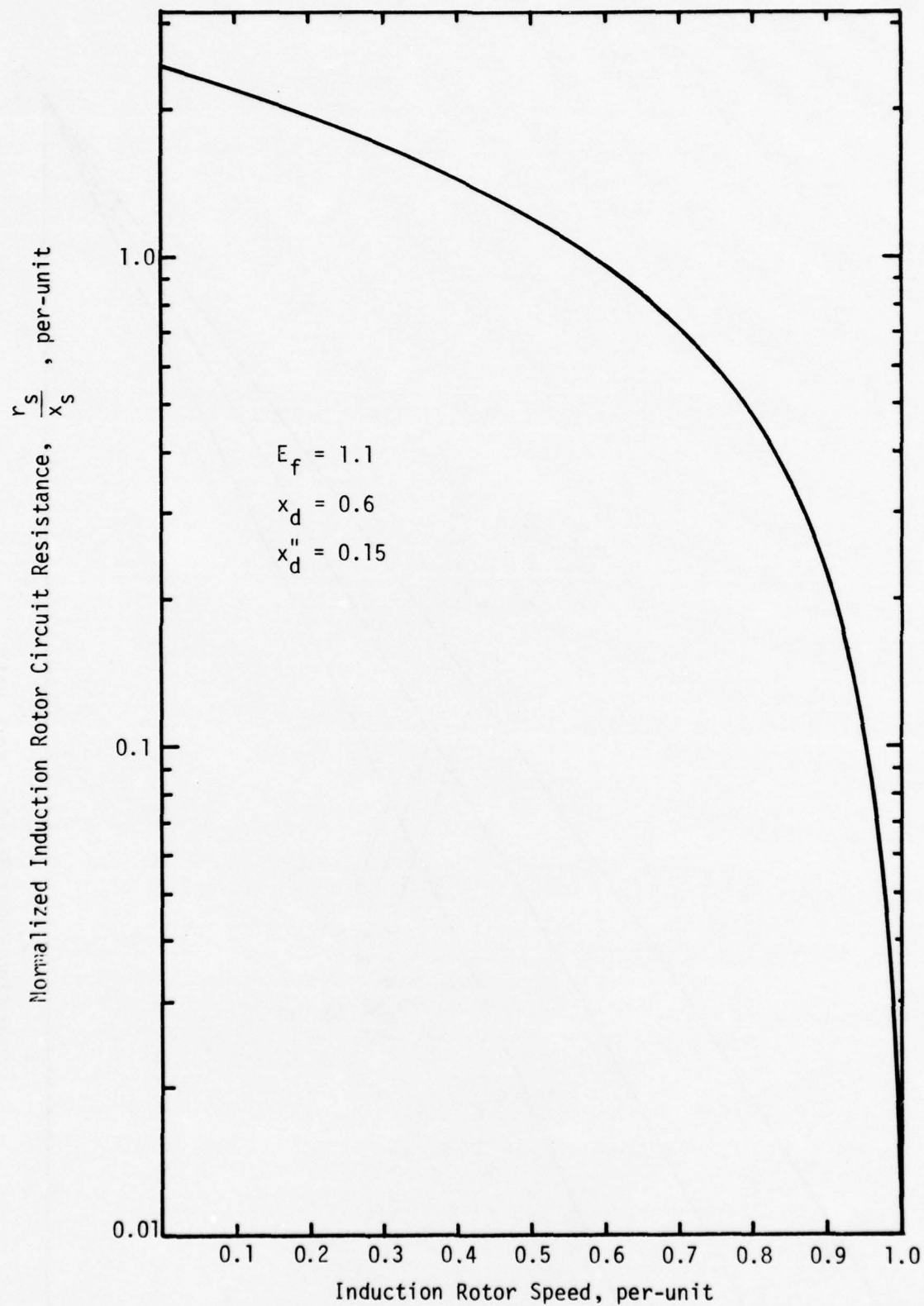


Fig. VII-8. Required Rotor Resistance For One Per-Unit Torque vs. Speed

Magnitude of Armature Current, $|I_a|$, per-unit

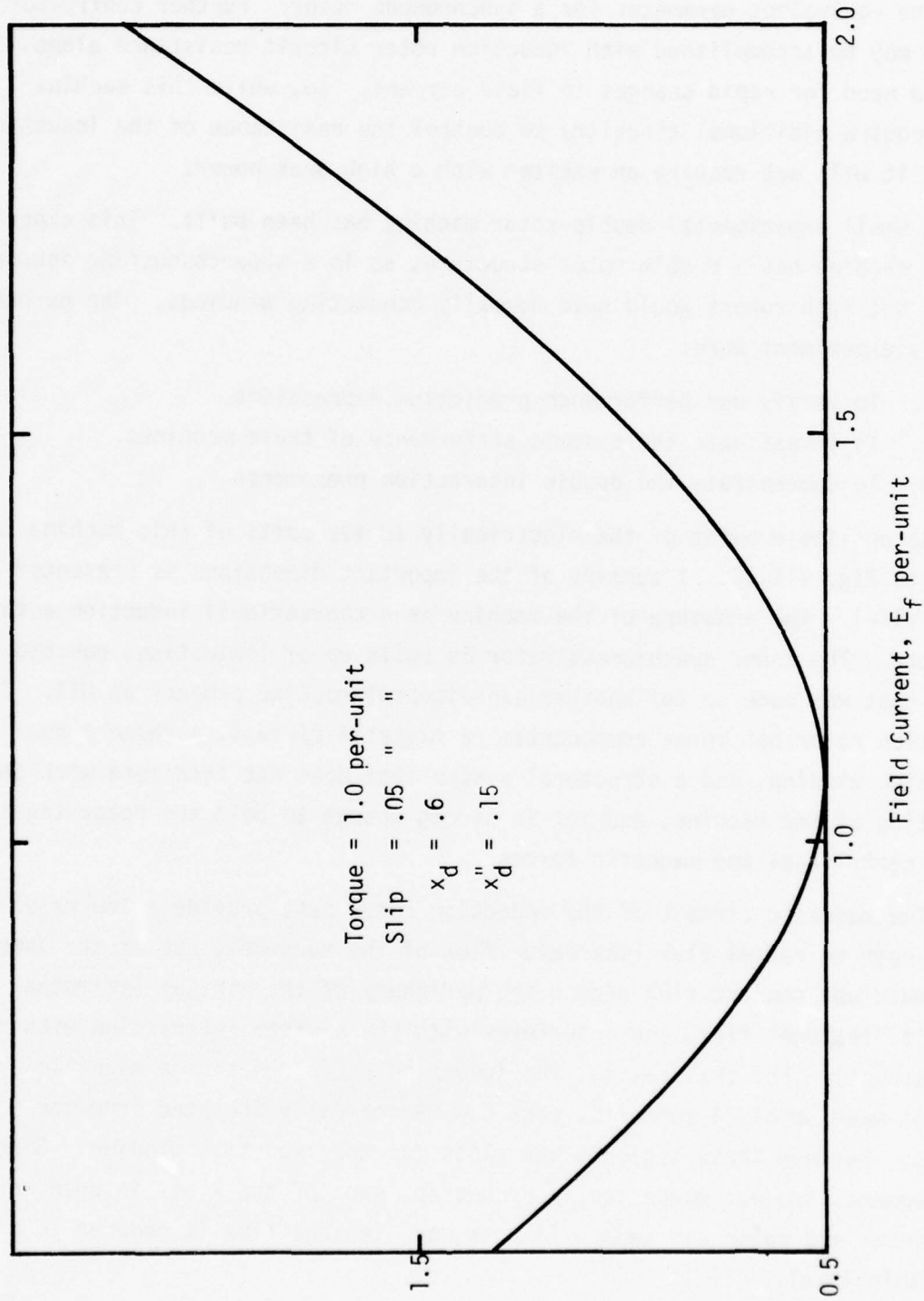


Fig. VII-9. Vee-Curve For A Superconducting Induction Motor, Constant Speed and Torque

than the equivalent parameter for a synchronous motor. Further control of torque may be accomplished with induction rotor circuit resistance alone, with no need for rapid changes in field current. So, while this machine will require additional circuitry to control the resistance of the induction rotor, it will not require an exciter with a high peak power.

A small experimental double-rotor machine has been built. This experimental machine has a double rotor structure, as in a superconducting induction motor, but both rotors would have normally conducting windings. The purposes of this experiment were:

1. To verify our performance prediction expressions.
2. To investigate the dynamic performance of these machines.
3. To demonstrate the double interaction phenomenon.

An outline drawing of the electrically active parts of this machine is shown in Fig. VII-10. A summary of the important dimensions is presented in Table VII-1. The armature of the machine is a conventional induction motor armature. The inner synchronous rotor is built up of laminations punched with a die that was made up for another experimental machine project at MIT. The induction rotor has three components: a magnetic circuit, a three phase induction winding, and a structural system that does not interfere with the operation of the machine, and yet is strong enough to hold the rotor together under centrifugal and magnetic forces.

The magnetic circuit of the induction rotor must provide a low reluctance path to radial flux (the major flux of the machine), but at the same time must not conduct flux around the periphery of the air gap (azimuthal flux is "leakage" flux, and interferes with the desired interaction within the machine). For this reason, the induction rotor contains a magnetic circuit made up of 24 segments, each one magnetically isolated from the others. Between these segments are slots for the induction winding. Since the segments are not magnetically connected, each of the slots is open to both inner and outer air gaps. In this way, leakage flux is reduced to a tolerable level.

The three phase induction winding is of more or less conventional design, resembling a three phase armature winding. This winding is connected to three slip rings. External resistors connected to the brushes

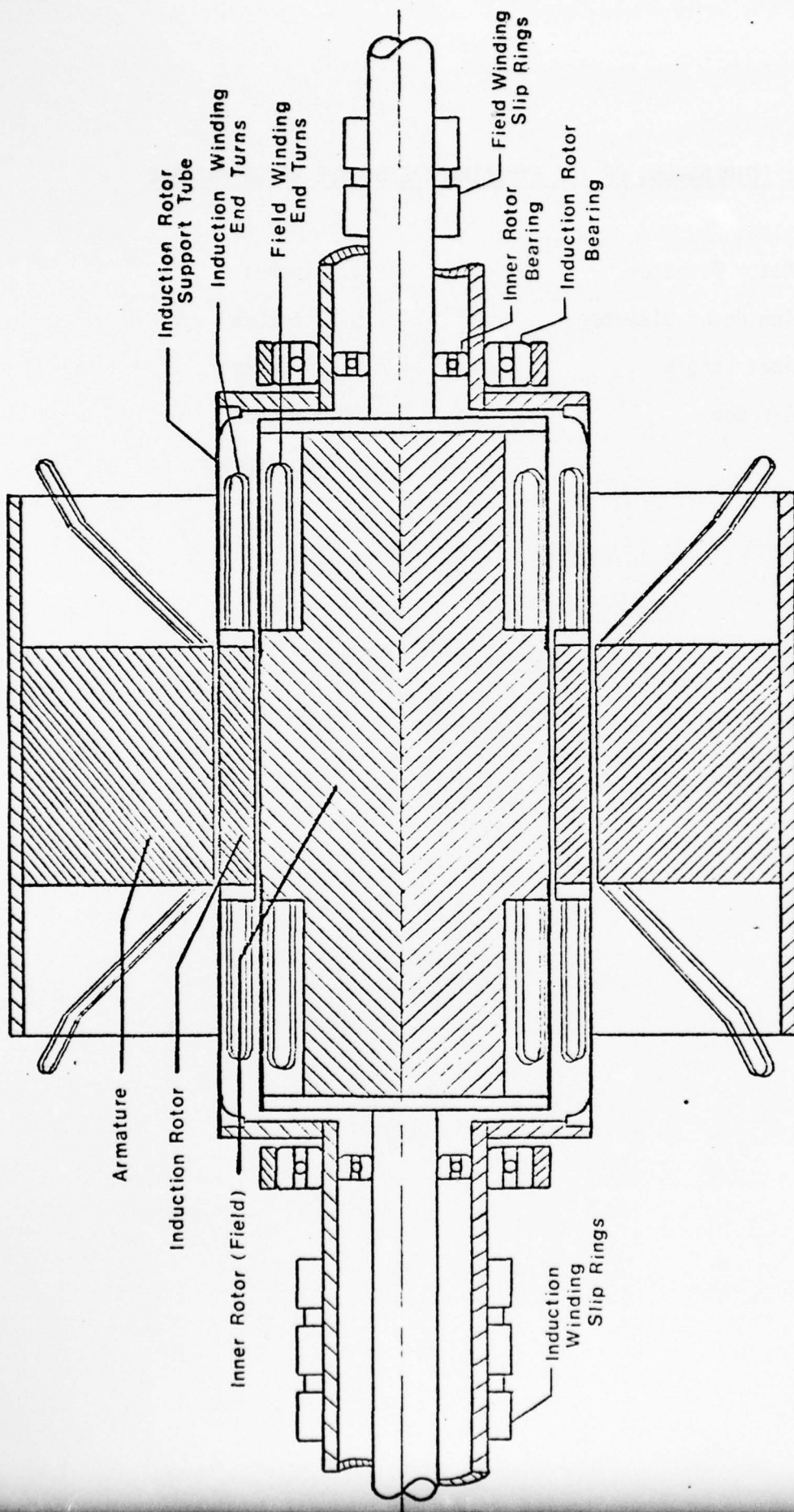


Figure VII-10 Assembled Machine Cross-Section
(Approximately 1/2 Scale)

TABLE VII-1: DIMENSIONS OF THE EXPERIMENTAL DOUBLE ROTOR MACHINE

Inner Rotor Diameter	4.5 inches
Induction Rotor Diameter	5.75 inches
Electrical Length	3.625 inches
Total Air Gap	.050 inches
Rating	2.7 horsepower

provide control for the machine. The induction winding is constructed in such a fashion that at some time in the future, if it becomes desirable, the rotor may be modified to convert the machine to a demonstration of the thyristor-switched low speed motor with reaction force cancellation. The structural system of the experimental machine induction rotor consists principally of a stainless steel tube, shrunk over the induction winding/magnetic circuit assembly. This thin tube is nearly transparent magnetically, and is thin enough (about .030") that the total air gap is not too large for satisfactory operation of the machine. A photograph of the parts of the experiment is shown in Fig. VII-11.

Operation of the experimental machine has shown us that:

1. Our performance expectations are generally confirmed. A set of torque-speed curves for the experimental machine is shown in Fig. VII-12.
2. We experienced difficulty in starting the synchronous rotor. The initial rotor design did not have an amortisseur winding, and so would not start itself. The rotor was modified to include a starting cage which turned out to be effective only when the field circuit was open-circuited.

From our experience with the model equipment, we have concluded that a pony motor will be required to accelerate the synchronous rotor for starting and for reversal. The reason for this is that the armature winding forms a very effective induction winding that produces braking torque at low rotor speed. If the armature is connected to a prime mover, the combination will form a low impedance at low frequency. If the field is excited during starting or reversal, it will drive currents in the armature at rotational frequency. During both starting and reversal the rotor turns quite slowly, and it is expected that this induction braking effect will simply prevent the rotor from turning.

Of course, a pony motor plus an armature circuit breaker will allow easy starting and reversal of the synchronous rotor. The pony motor will not have to be very large because the field rotor is quite light, and the armature is expected to be connected through a circuit breaker anyway.

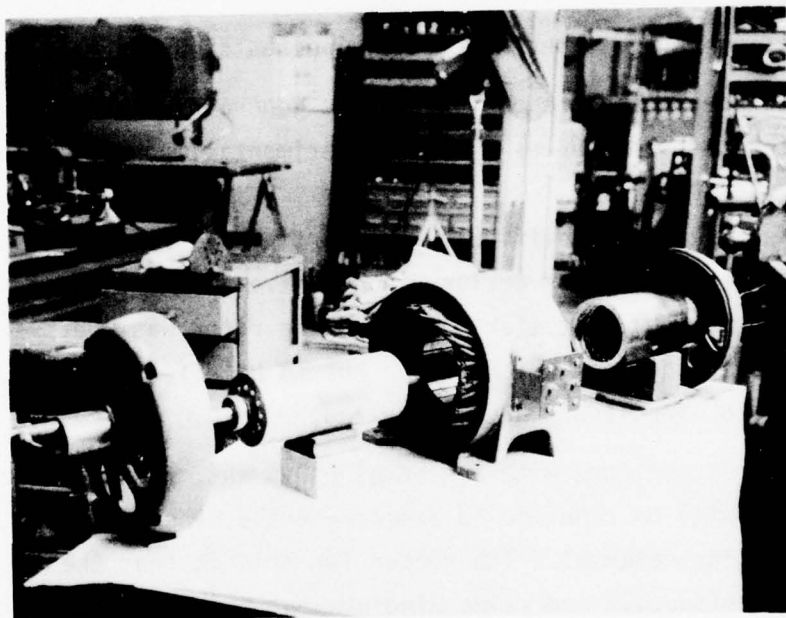


Fig. VII-11. Experimental Double Rotor Motor

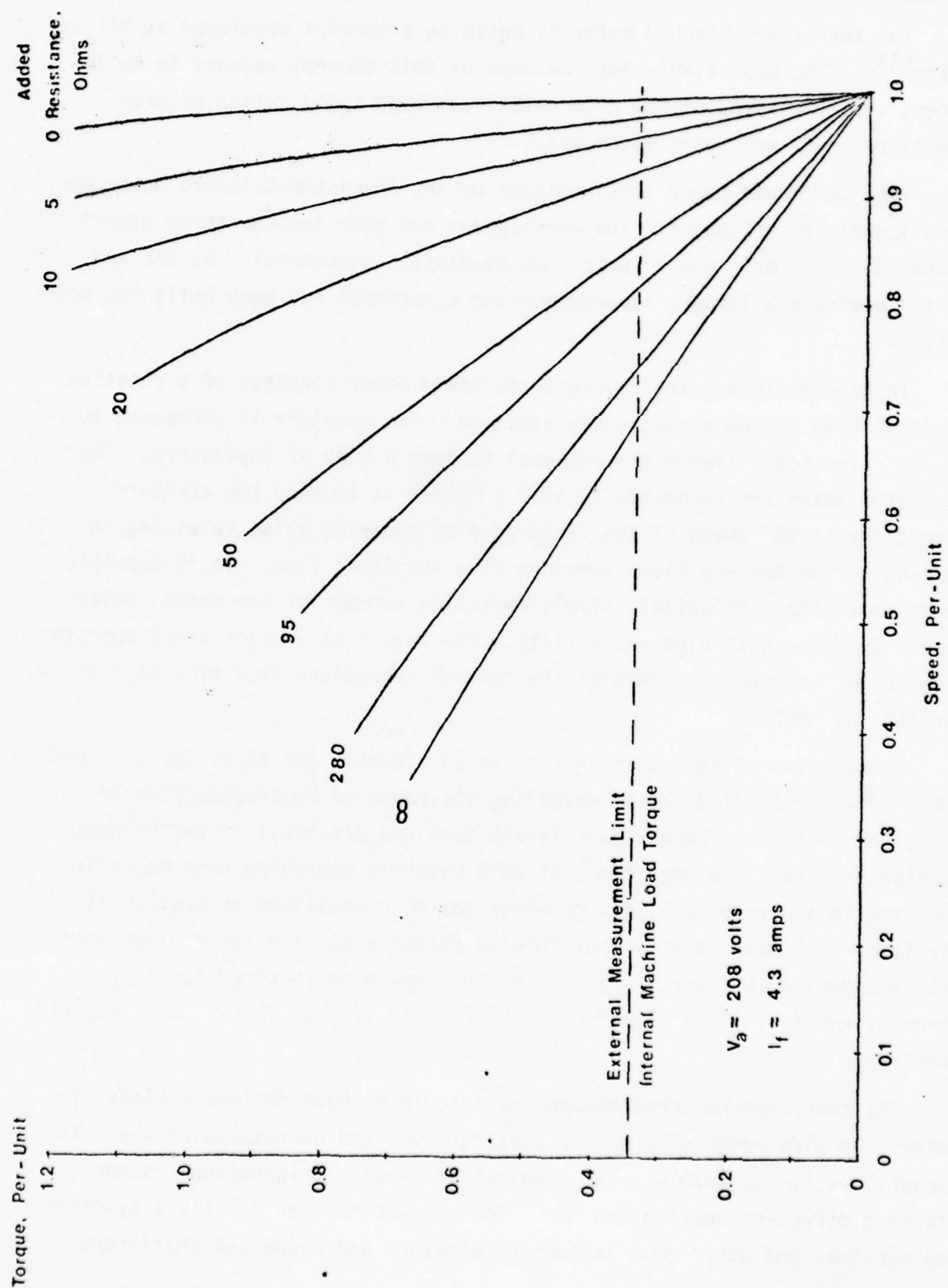


Figure VII-12 Induction Rotor Torque vs. Speed
as a Function of Added Winding Resistance

VIII. THYRISTOR SWITCHED MOTOR

The thyristor-switched motor is based on a concept developed at MIT by Smith⁽¹⁴⁾. The most likely applications of this concept appears to be in large, variable speed drives with relatively high speed ratios between generator shaft and drive motor shaft.

Work performed under this contract on the thyristor-switched motor has been largely experimental. The development has gone through three experimental designs, only one of which was completely successful. At the end of the contract a larger, superconducting experiment had been built but not tested.

In general terms, the thyristor-switched motor consists of a rotating field winding inside a stationary armature. The armature is connected to an ac line (most likely three-phase) through a bank of thyristors. The thyristor gates are connected in such a manner as to keep the armature magnetic axis 90° ahead of the field-winding magnetic axis, resulting in maximum torque for any given armature flux and field flux. It is possible to do this with a relatively simple switching scheme for the gates, which should function with high reliability. The result is a motor which operates from an ac source yet exhibits the control characteristics of a separately excited dc motor.

In addition to the advantages of speed control, the thyristor-switched motor offers the potential of extending the range of superconducting low speed ac motors to lower power levels than are practical in synchronous machine designs. The importance of pole pitch in achieving high magnetic coupling in air-core multipole machines has been explained in Section IV. Thyristor switching makes it possible to design a machine for a given speed and frequency with fewer, larger poles than would be required for a synchronous machine. Thus diameter may be reduced without sacrifice of magnetic coupling.

The thyristor-switched concept as described above defines a class of motors. A wide range of armature constructions and corresponding thyristor connections is achievable. The simplest of these configurations is the standard direct-converting (no dc link) cycloconverter driving a synchronous machine, but other combinations of armature and connected thyristors

have not yet been investigated or widely discussed. Many of these less standard configurations appear to offer advantages over conventional cycloconverter systems, but require non-standard armatures, which have not normally been considered. Superconducting rotating-field machines employ air-gap armatures which give the designer unprecedented freedom to consider novel armature configurations. Therefore, design of a thyristor-switched motor should optimize the armature and the thyristor network as a system.

A schematic picture of the type of thyristor-switched motor investigated is shown in Figure VIII-1. The armature winding is connected in a closed loop configuration, similar to that of a dc motor. The switching networks connected to each node point consist of two half-wave thyristor rectifier networks, one adapted to carrying current into the node, the other adapted to carrying current out of the node. A rotor position sensor is used to establish which nodes are to be active at any given time.

All three of the experimental designs were based on a small synchronous machine that had been constructed for another purpose. The chief advantage of this machine was that it had accessible, readily reconnectable end turns, and was thus easily adapted.

The first experimental design was an attempt at a highly simplified switching scheme. It employed a mechanical signal level commutator which was used to connect line voltage to the thyristor gates through a diode and resistor network, Fig. VIII-2. This first experiment used a seven-phase armature configuration.

Major problems were encountered with this first experiment, resulting in sudden and catastrophic thyristor failures. These thyristor failures were caused by inappropriate firing of thyristors which would leave two thyristors in series conducting directly between two supply phases. This inappropriate firing is thought to have been caused by:

1. Spurious conduction in the signal level commutator, caused by contamination from the carbon brushes,
2. Inordinate thyristor gate sensitivity due to the very wide range of thyristor gating signals used,
3. Improper thyristor firing by rate of change of forward voltage, in turn caused by the method of firing and by the lack of snubbing

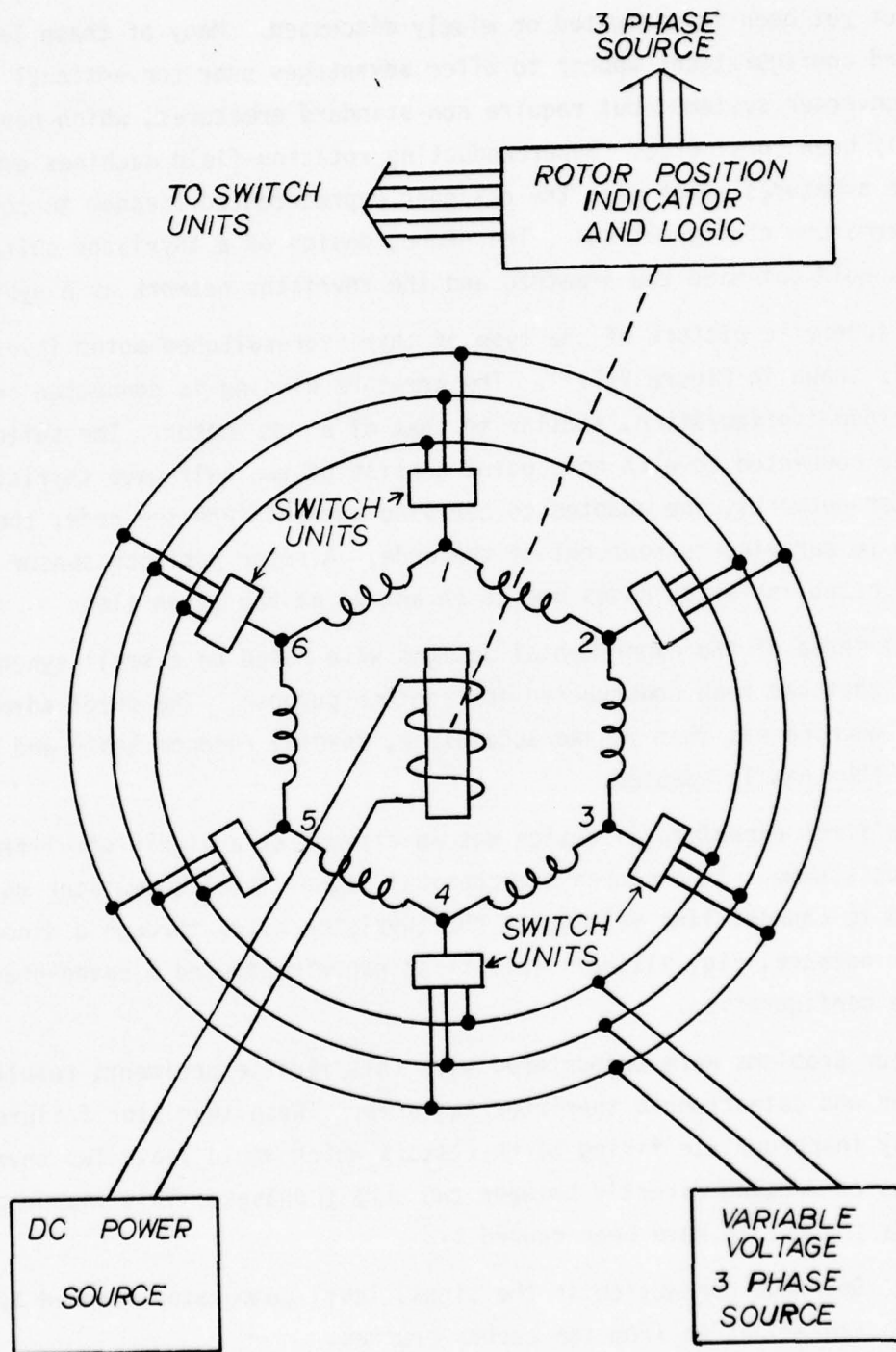


Fig. VIII-1. Generalized SCR commutated AC motor. By sensing the rotor position the appropriate switch units are triggered to maintain a torque angle of ninety degrees.

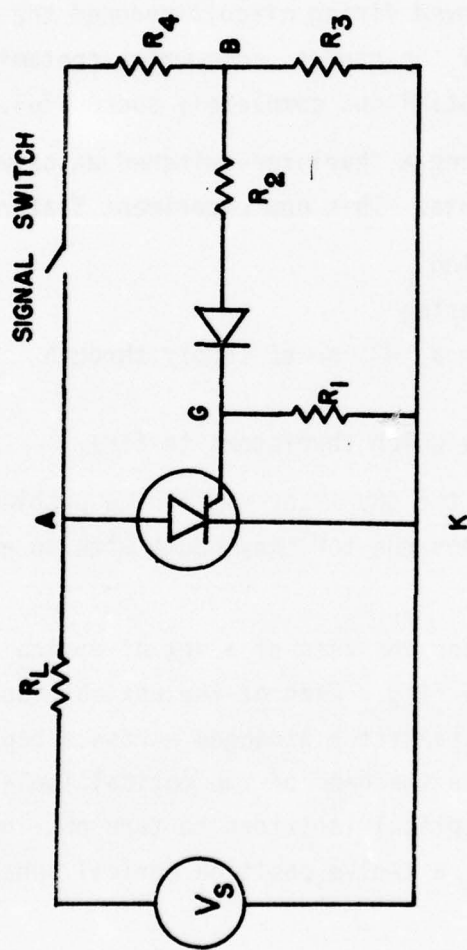


Figure VIII-2 Proposed SCR trigger circuit. $R_1 = 1 \text{ k}\Omega$,
 $R_2 = 10 \text{ k}\Omega$, $R_3 = 100 \text{ k}\Omega$, $R_4 = 200 \Omega$.

circuits.

The second experimental effort rectified problems two and three. The range of thyristor gate signals was reduced through the use of a Zener-diode-regulated capacitor discharge firing circuit. The dv/dt problem was eliminated through the addition of appropriate snubbers. Figure VIII-3 shows the final circuit used for thyristor firing.

Unfortunately, while this improved firing circuit reduced the misfiring problem, it did not eliminate one of the causes, commutator contamination. For this reason the experiment was still not completely successful.

The third attempt at implementing a thyristor-switched motor was a major departure from the earlier experiments. This new experiment featured:

1. A six-phase motor connection
2. Optical rotor position sensing
3. Thyristor gate firing from a dc power supply through pulse transformers.
4. Digital logic to determine which thyristors to fire.

This experiment has eliminated the thyristor mis-firing problem, and has resulted in a motor which has been run for many hours with no apparent problems in the electronics.

The optical rotor position sensor consists of a set of optical isolator devices arranged around a stationary ring. Each of the optical isolators is a photo-emitting diode and a photo transistor arranged across a gap. A thin disk attached to the rotor rotates in the gaps of the optical isolators. A gap in this disk causes one of the optical isolators to turn on, indicating rotor position. Figure VIII-4 shows a twelve position optical sensor built for the large experiment.

An analog comparator is used to determine which source phase is most positive (or negative). These signals, plus the rotor position signals and a clock are combined in OR gates as shown in Figure VIII-5 to produce firing signals for each of the thyristors.

The characteristics of the drive system produced using this scheme are similar to those of a separately excited dc motor, as shown in Figs. VIII-6 and VIII-7.

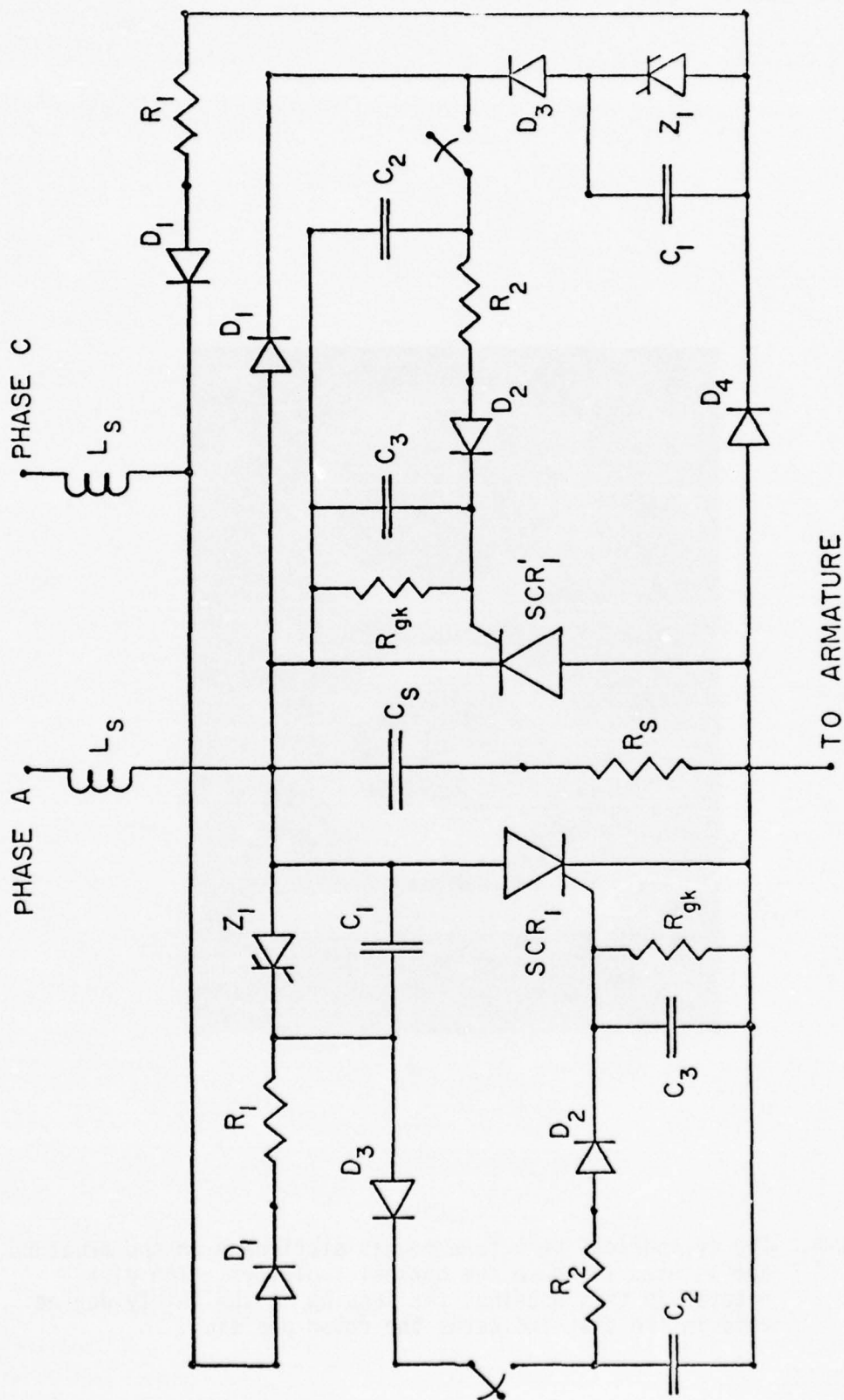


Fig.VIII-3 Complete circuit topology associated with a back-to-back pair connected to phase A.

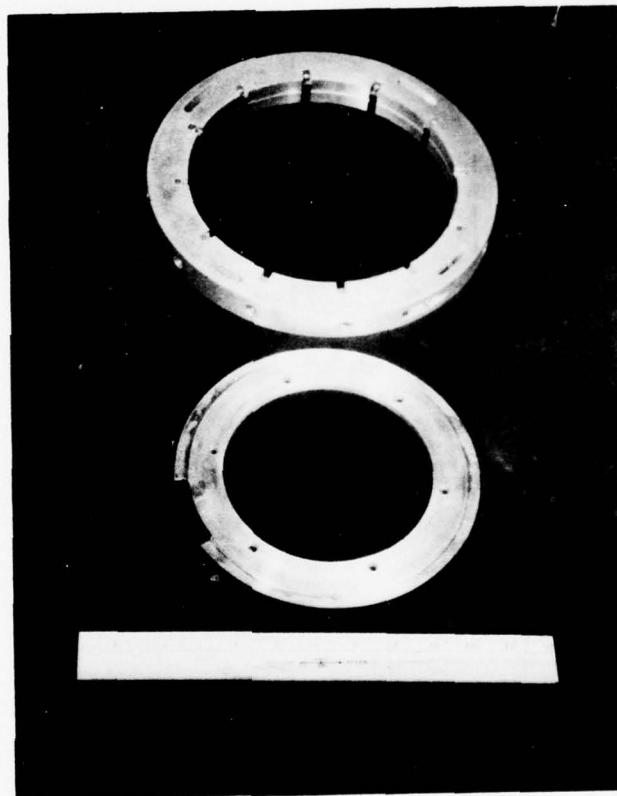


Fig. VIII-4. The cylindrical structure mounts stationary on the armature and is used to house the optical isolators. The disk rotates in this housing, the sensing of the thirty degree void in the disk indicates the rotor position.

*Sprague #11Z200

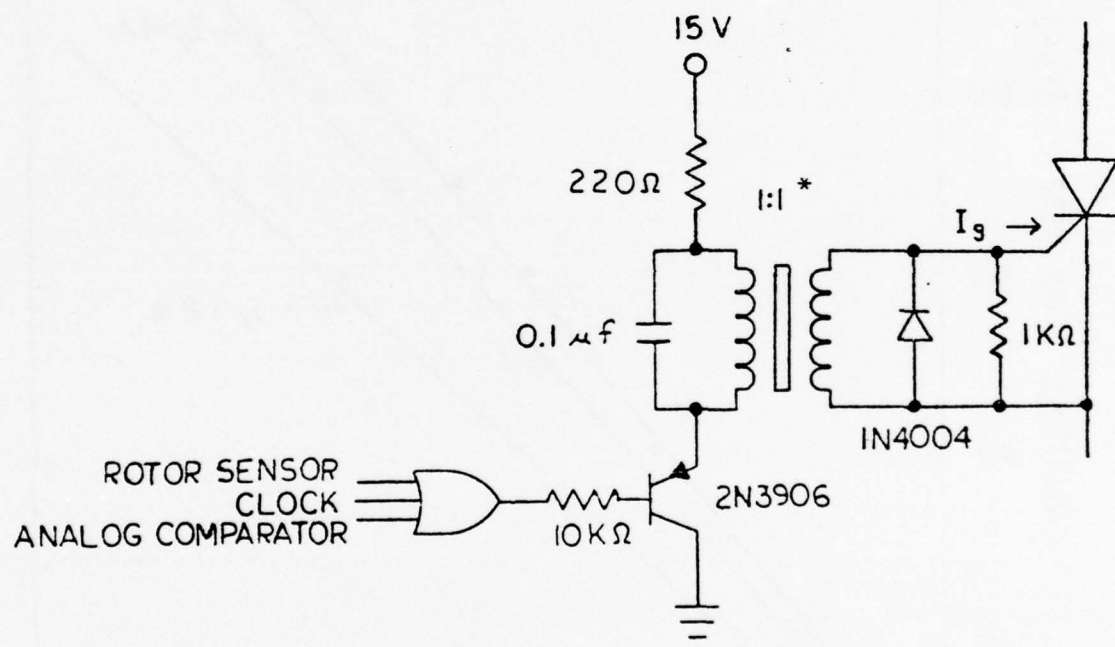


Fig. VIII-5 Thyristor Firing Circuit

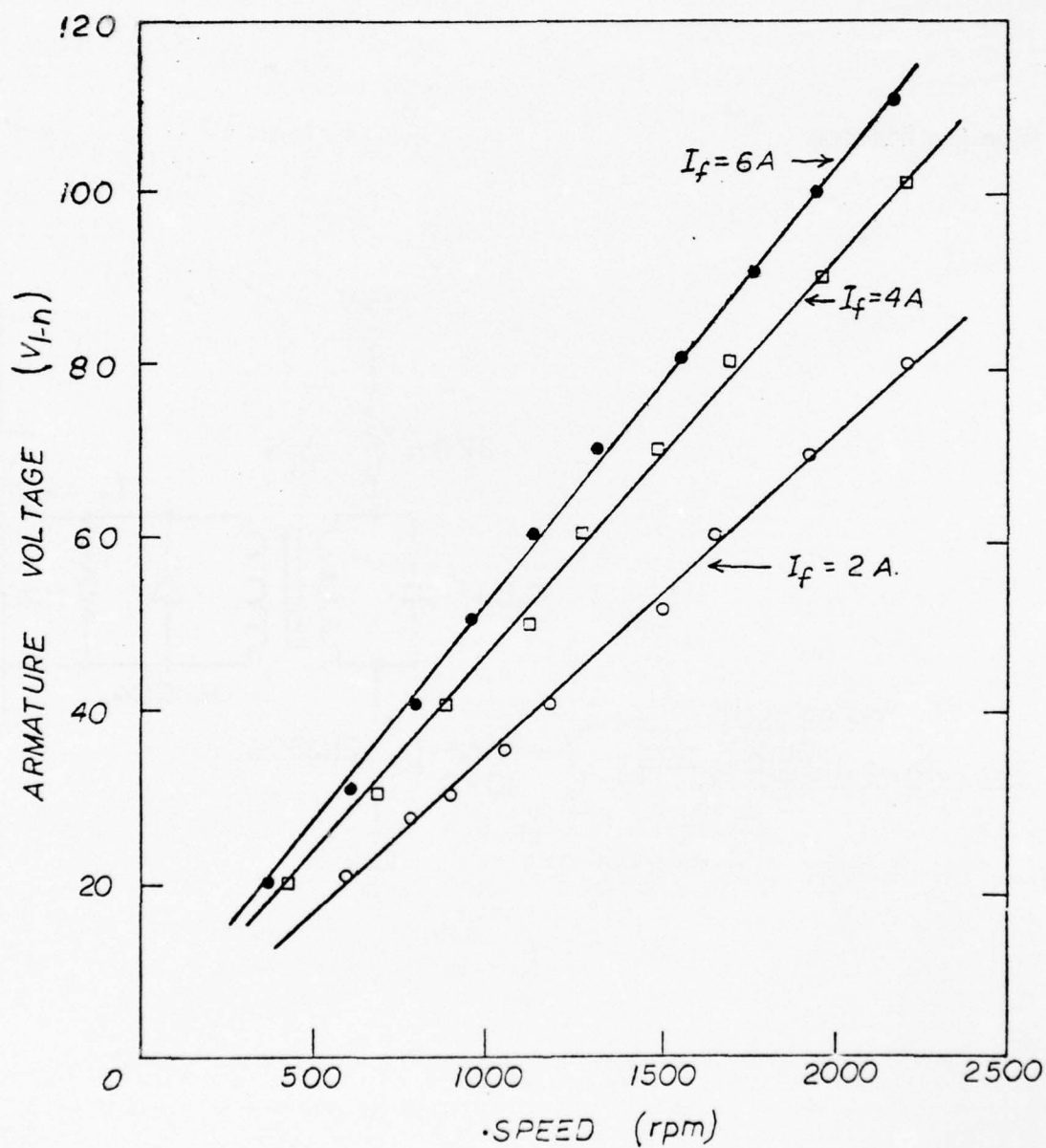


Figure VIII-6. Results of speed versus applied armature voltage tests for the SCR commutated AC motor.

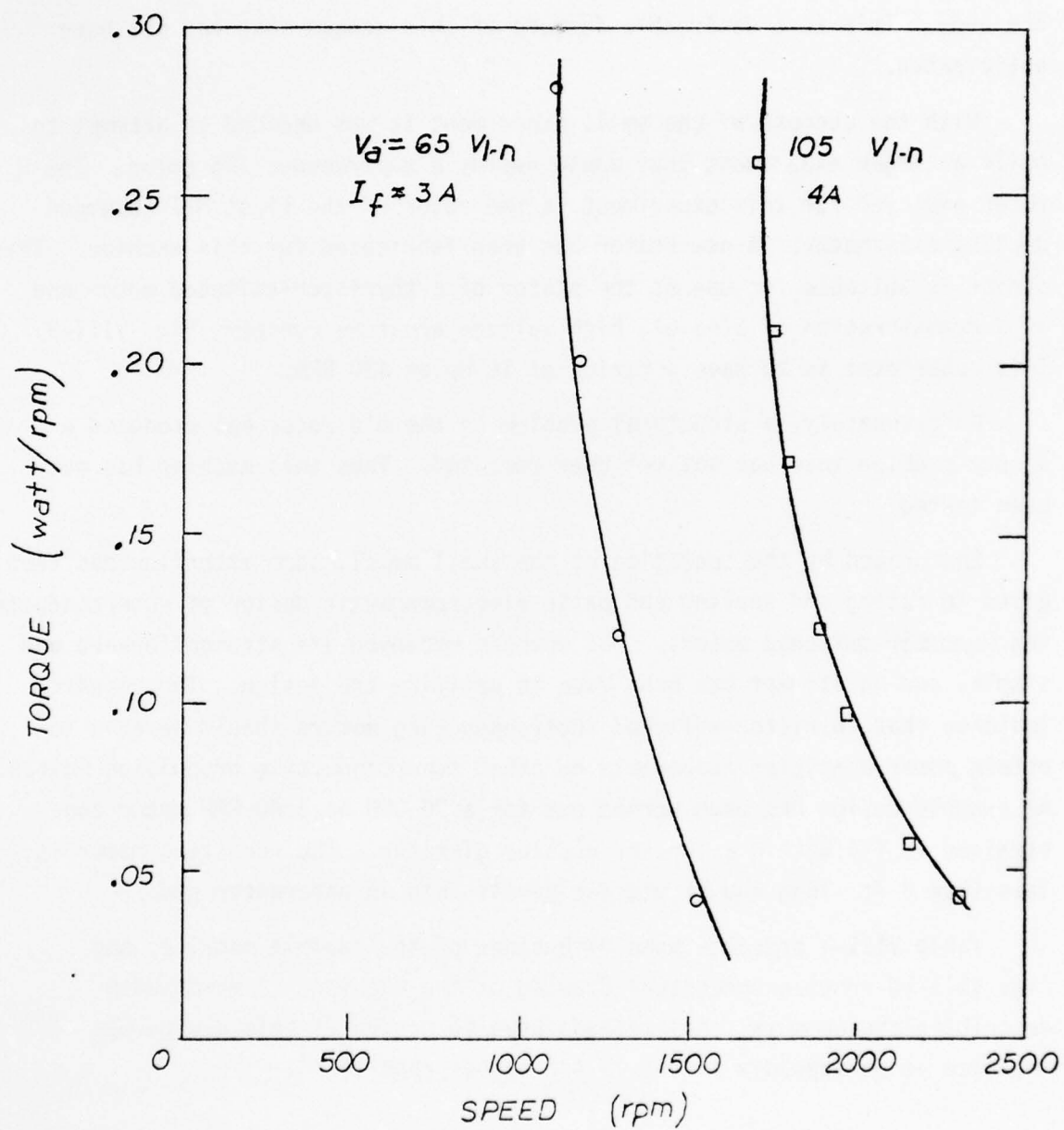


Fig. VIII-7 Speed versus torque curves for the experimental SCR commutated AC motor.

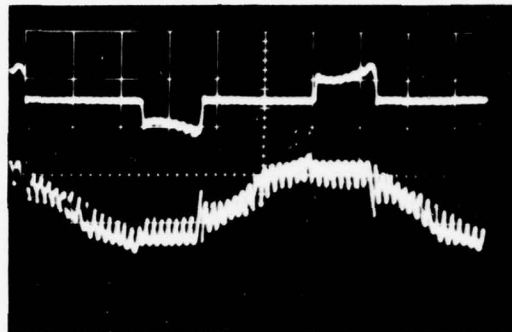
Figure VIII-8 shows voltage and current waveforms for the small experimental motor. Note the very rapid commutation of current in the line feeding the node. This is a desirable feature of this scheme that had not been anticipated.

With the success of the small experiment it was decided to attempt to build a larger experiment that would employ a superconducting rotor. The rotor employed for this experiment is the rotor of the first MIT superconducting alternator. A new stator has been fabricated for this machine. This stator is suitable for use as the stator of a thyristor-switched motor and as a demonstration of a novel, high voltage armature concept, Fig. VIII-9. This experiment is to have a rating of 10 Hp at 420 RPM.

Unfortunately, a structural problem in the old rotor has produced a vacuum problem that has not yet been remedied. Thus this machine has not been tested.

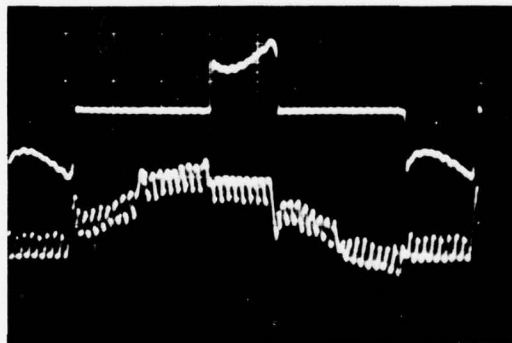
Encouraged by the operation of the small model, some attention has been given to rating and scaling and basic electromagnetic design of superconducting thyristor-switched motors. The methods employed are straightforward and simple, and no attempt has been made to optimize the design. The results indicate that thyristor-switched superconducting motors should be able to obtain power densities comparable to other superconducting propulsion motors. An example design has been worked out for a 20,000 hp 1200 RPM motor constrained to fit within a 1 meter outside diameter. The resulting motor is less than 6 ft. long and should fit nicely into an underwater pod.

Table VIII-1 presents some dimensions of the example machine, and Fig. VIII-10 shows a conceptual drawing of the machine. A memorandum describing the computational methods used to arrive at this design was included as an appendix in the 1974 progress report⁽⁹⁾.



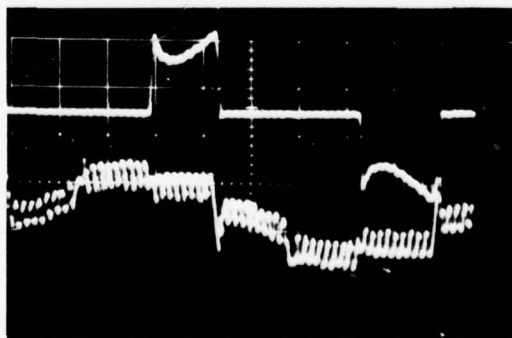
current node 1
4 amps/div

voltage node 1
100 V/div



current node 1
4 amps/div

voltage node 1
100 V/div



current node 1
4 amps/div

voltage node 1
100 V/div

Fig. VIII-3. Armature current and voltage of node 1, note rapid commutation of the 'last' thyristor.

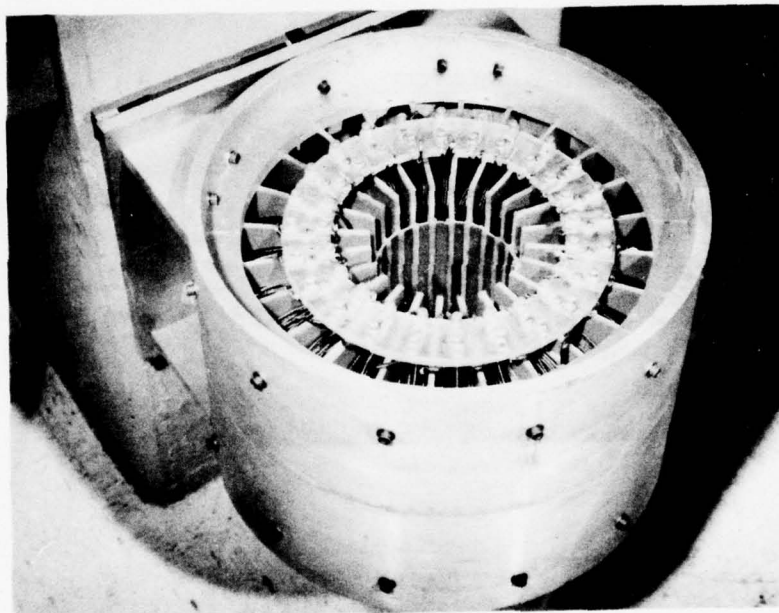


Fig. VIII-9. Toroidal armature used in the experimental SCR commutated AC motor.

TABLE VIII-1

Field outside radius	$R_{fo} = .1947 \text{ m} = 7.66 \text{ inches}$
Field inside radius	$R_{fi} = .1360 \text{ m} = 5.35 \text{ inches}$
Field thickness	$\Delta f = .0587 \text{ m} = 2.31 \text{ inches}$
Field-armature gap	$g = .0381 \text{ m} = 1.5 \text{ inches}$
Armature outside radius	$R_{ao} = 0.357 \text{ m} = 14.06 \text{ inches}$
Armature inside radius	$R_{ai} = 0.232 \text{ m} = 9.16 \text{ inches}$
Armature thickness	$\Delta a = 0.125 \text{ m} = 4.90 \text{ inches}$
Outside radius	$R_{os} = 0.5 \text{ m} = 19.68 \text{ inches}$
Iron thickness	$\Delta i = 0.143 \text{ m} = 5.62 \text{ inches}$

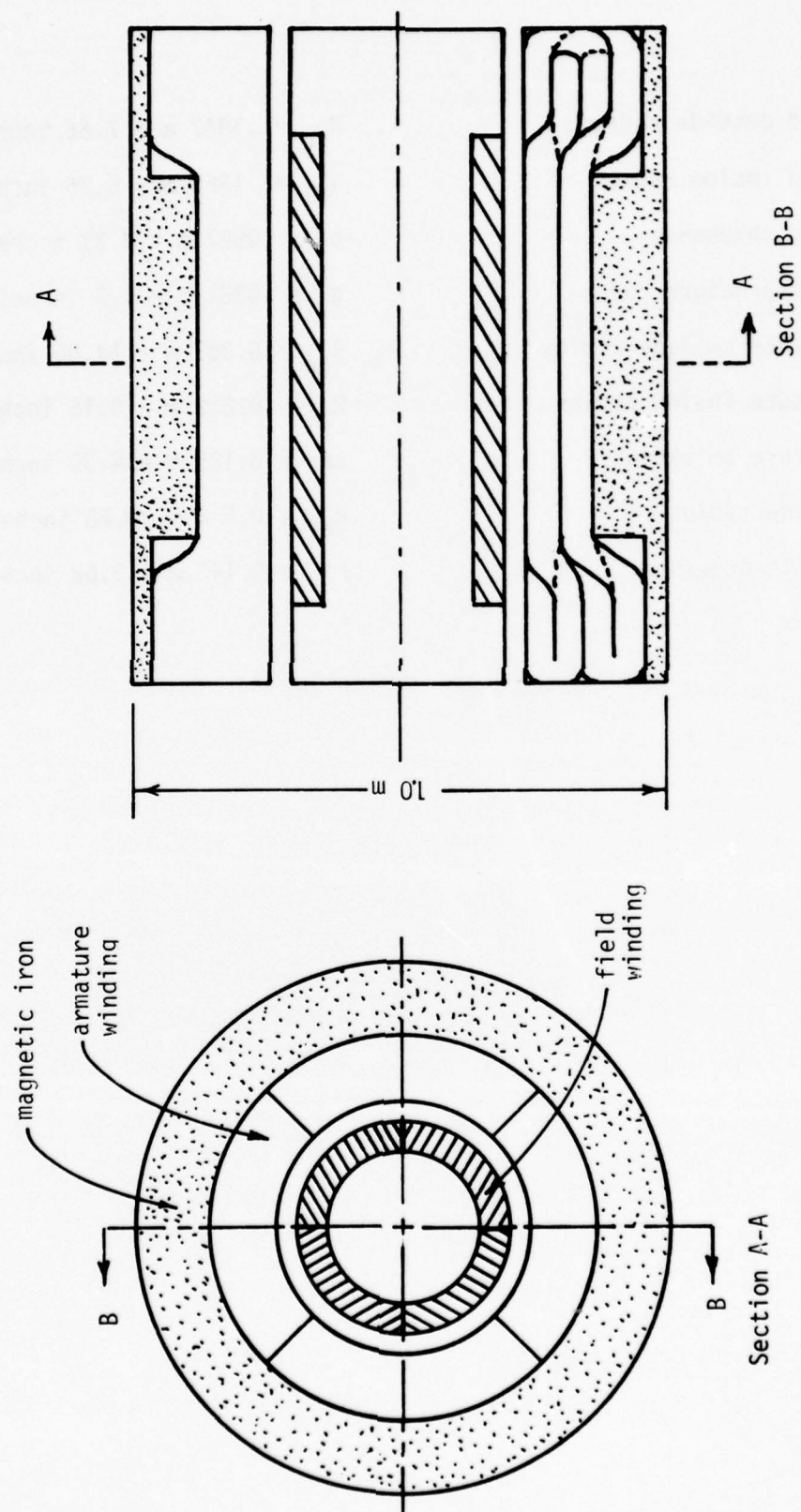


Figure VIII-10 Conceptual Drawing, 20,000 hp 1200 RPM Thyristor-Switched Motor

IX. Refrigeration Requirements of AC Superconducting Machines for Ship Propulsion

This study establishes and documents procedures for "first order" predictions of helium cooling requirements of superconducting AC machines. Five modes of heat transport to the cryogenic regions of superconducting rotors are considered and in each case a simple numerical procedure is developed for estimating the refrigeration requirements. In addition design suggestions are given for reducing liquid helium consumption.

The five modes of heat transport considered are:

1. Thermal conduction through mechanical supports.
2. Thermal radiation across the vacuum gap.
3. Cryogenic current leads.
4. Eddy current heating in cylindrical shells due to time-varying magnetic fields.
5. Liquid helium transfer line losses.

The study of conduction through mechanical supports started with the simple case of direct conduction to the cold end of the support. A support continuously cooled with a single stream of gas flowing along the support from the cold to the warm end was studied as a limiting case. The results show that the gas cooled support has a cold end heat leak of about 5 per cent of that for the simple support when the helium flow is self-sufficient. That is the helium flow rate is equal to the helium boil off rate associated with the conduction from the cold end of the support. If the gas flow is about 20 per cent more than the self-sufficient flow as a result of other heat flux to the helium, the cold end heat leak from the support is reduced to a negligible value.

A more practical method of gas cooling a support may be to cool at several discrete heat stations located along the support. Optimum designs have been worked out numerically for one to five stations for six different materials commonly used for cryogenic supports and the results are given in detail in the report⁽¹¹⁾. Although the cooling effectiveness increases continuously with the number of heat stations, the results show that about 85 to 90 per cent of the gain has been achieved with only four stations.

The study of radiation heat transfer across the air gap consisted of the

application of well known radiation heat transfer relations to three simple cases: No radiation shield, one gas cooled radiation shield, and two gas cooled radiation shields. Representative data was collected and employed in the calculations. The effectiveness of the three shielding systems is conveniently summarized in the report ⁽¹¹⁾ in terms of the liquid helium requirement per unit of surface for representative conditions in superconducting machine rotors. The use of multilayer insulation is shown to be quite effective when used in connection with gas cooled shields. The reduction in heat flux is by a factor of about 5 to 10 for reasonable thicknesses of insulation. The multilayer is most effective on the room temperature surface. In high speed rotor applications the use of multilayer insulation is still desirable in spite of some degradation resulting from the centrifugal acceleration.

The study of cryogenic current leads included a survey of the extensive literature on the subject and the derivation of various theoretical limits on the design of the leads. The recommended design for current leads is presented in terms of the conductor cross section divided by the lead length, A/L. In the recommended design A/L is selected to give a minimum low temperature heat leak for a given design current. The parameter A/L is also selected to prevent thermal instability or burn up. For a pair of copper leads the recommended design is

$$\frac{A}{L} = (2)10^{-5} \left(\frac{I_{\max}}{\text{amperes}} \right) \frac{\text{cm}}{\text{pair}}$$

The recommended helium coolant flow rate for this design is

$$\dot{m} = (5.03 \pm 1.28)I \frac{\text{liters/hr/pair}}{1000 \text{ amperes}}$$

The problem of eddy current heating of the cryogenic parts of the rotor of an AC machine was considered in terms of two dimensional currents induced in a conducting shell of tubular shape by two dimensional changes in the magnetic field expressed in rotor coordinates. Shells of high conductivity and of low conductivity are used to represent eddy current shields and rotor structural tubes, respectively. The alternating fields considered are first spatial harmonic negative sequence fields, fifth spatial harmonic

fields and seventh spatial harmonic fields. The attenuation of the AC fields by the eddy current shield around the rotor is included in the calculations. A simplified approximation is employed for estimating the eddy current losses associated with ramping the field current. The complex problem of losses in the superconductor is not considered. Numerical results for representative cases of AC machines are given in graphical form in the report⁽¹¹⁾ for quick estimates of the heating.

The short and simplified treatment of the complex problem of eddy current heating is perhaps adequate for preliminary estimates; however, design calculations should be based on the original developments by Luck⁽¹⁸⁾ and Keim⁽¹⁹⁾ which are also incomplete in a number of significant ways.

The refrigeration requirements for liquid helium transfer systems have been derived and include heat leaks in the transfer tubes, standard bayonet joints and valve stems. These are essentially additional cases of the support heat leak and radiation heat leak presented previously. The special case of the additional heat leak resulting from the relative rotation in a rotatable bayonet coupling is calculated by the method of Lee⁽²⁰⁾.

A numerical example has been worked out to illustrate the use of the methods developed for estimating liquid helium requirements for AC superconducting machines. The MIT 3-MVA superconducting machine was selected for the example and the results are given in detail in the report⁽¹¹⁾.

X. SUMMARY CONCLUSIONS

In the course of this program theoretical and experimental analysis has been made for several superconducting A.C. machine concepts suitable for ship drive application. These concepts include high speed generators; low speed, multipole synchronous motors; torque compensated motors, including the superconducting induction motor; and a novel line-commutated thyristor switched motor. In addition, a study was made of the cooling requirements for A.C. superconducting machines, especially the requirements for torque tubes and current carrying cryogenic leads. It appears to us that a combination of some of these concepts will provide a good way of producing lightweight, high performance electric drive systems.

As we expected from other work, superconducting generators promise to have substantial advantages over conventional generators, in terms of size, weight, and efficiency.

Contrary to expectations, we found that superconducting windings can be used advantageously in high-power, low speed motors with many electrical poles, providing that the design has adequate pole pitch.

Two concepts which reduce or eliminate torque on the superconducting field winding, and thus reduce refrigeration requirements, were studied. While it appears that such machines can operate successfully, our study of refrigeration requirements indicates that, for most applications, the degree of reduction of refrigeration afforded is not really needed.

One of the torque compensated schemes, the superconducting induction motor, has interesting and favorable control characteristics which make it a good candidate for some applications.

The line commutated thyristor switched machine concept appears to be a good way of producing a high efficiency, variable speed drive. It allows the number of poles on the motor to be picked for optimum motor size, and will thus result in a very compact drive system.

The study of cooling requirements has shown that properly designed machines will not have prohibitive cooling requirements for most applications.

It appears to us that the concepts most likely to prove valuable for ship drive motors are the thyristor switched motor and the superconducting induction motor. The thyristor switched machine, in conjunction with a superconducting generator, would provide a high power density, high efficiency drive system with excellent control characteristics, including a very wide range of shaft speed ratio. The superconducting induction motor may see use in applications in which a large shaft speed ratio is not needed (3:1 or less) and in which the complexities of a thyristor drive are not desired.

We would recommend that the state of the art is ready for sizeable demonstration experiments for each of these machine concepts. The experiments should be superconducting, to show features associated with iron-free machines, and should be at a reasonable power level, perhaps in the range of one hundred kilowatts.

We believe that these two machine concepts show excellent promise for real application. A serious comparison with electric drive systems that were not considered in our study (we specifically did not consider acyclic machines) is in order.

XI. Reports, Papers, Theses, and References

This section lists all reports, papers and theses that document the research done and results obtained under the contracts. Each of these reports, papers and theses is reviewed in the next section. Copies of any of these documents which are not available elsewhere can be obtained from Cryogenic Engineering Laboratory, Room 41-202, Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139.

1. "Analysis of a Superconducting Generator for Ship Propulsion", Kutsal A. Denizmen, S.M. and O.E., May 1973. (MIT Thesis).
2. "Application of Superconducting Motors to Super Cavitating Hydrofoil Propulsion", John Michael Solan, S.M. and O.E., June 1973. (MIT Thesis).
3. "Preliminary Analysis of the Double Rotor Induction Motor", J. L. Kirtley, Jr., Electric Power Systems Engineering Laboratory (MIT), Internal Memorandum No. 23, Oct. 2, 1973.
4. "Superconducting Electrical Machines for Ship Propulsion", J. L. Smith, Jr., J. L. Kirtley, Jr., T. A. Keim, P. Thullen, Research Progress Report to Office of Naval Research, October 15, 1973, Contract No. N0014-67-A-0204-0068.
5. "Analysis and Design of Multipole Superconducting Rotating Electric Machines", Joseph Vito Minervini, S.M., January, 1974. (MIT Thesis).
6. "Design and Construction of an Electrically Commutated AC Motor with a Fixed Torque Angle", Luis I. Cabezón G., S.B. and S.M., July, 1974. (MIT Thesis).
7. "Superconducting Rotating Machines", J. L. Smith, Jr., J. L. Kirtley, Jr., and P. Thullen. IEEE Trans. on Magnetics, Vol. MAG-11, No. 2, March, 1975, pp. 128-134.
8. "Multipole Superconducting Electric Motors for Ship Propulsion", P. Thullen, T. A. Keim, and J. Minervini, IEEE Trans. on Magnetics, Vol. MAG-11, No. 2, March 1975, pp. 653-656.
9. "Superconducting Electrical Machines for Ship Propulsion", J. L. Smith, Jr., and T. A. Keim, Research Progress Report to Office of Naval

Research, Contract No. N0014-67-A-0204-0068, October 22, 1974.

10. "A Superconducting Synchronous Torque-Compensated Motor for Naval Applications", Donald M. Reynerson, S.M. and N.A., June 1975. (MIT Thesis).
11. "Refrigeration Requirements of AC Superconducting Machines for Ship Propulsion", A. Bejan, Report to Office of Naval Research, Appendix D to Progress Report, Aug. 4, 1975, Contract No. N00014-75-C-0497.
12. Progress Report to Office of Naval Research, "Superconducting Machines For Ship Propulsion", Aug. 4, 1975, Contract No. N00014-75-C-0497.
13. "An SCR Commutated D.C. Motor", John A. Redding, S.M., September, 1975. (MIT Thesis).
14. "A-C Powered Thyristor Switched Electrical Motors Having Superconducting Fields", J. L. Smith, Jr., U.S. Patent No. 3,909,684, September 30, 1975.
15. "Design, Construction and Testing of an Experimental Dual-Rotor Induction Motor", J. W. Stetkar, S.M., Department of Nuclear Engineering, April, 1976. (MIT Thesis).
16. "The Rotating Air Gap Armature Machine as a Superconducting Induction Motor for High Speed Ship Propulsion", Frank C. Rumore, S.M., August, 1976. (MIT Thesis).
17. "An Improved Design of a SCR Commutated D.C. Motor", J. Frederick Donohoe, S.M., February 1977. (MIT Thesis).
18. "Electromechanical and Thermal Effects of Faults Upon Superconducting Generators", David L. Luck, Ph.D., Department of Electrical Engineering, June, 1971. (MIT Thesis).
19. "Design and Construction of an Excitation System For a Superconducting Alternator", Thomas A. Keim, Sc.D., Department of Mechanical Engineering, January, 1973. (MIT Thesis).
20. "Continuous Transfer of Liquid Helium To a Rotating Dewar", W. David Lee, S.B. and S.M., Department of Mechanical Engineering, June, 1970. (MIT Thesis).

XII. CRITICAL REVIEWS OF REPORTS, PAPERS AND THESES

This section critically reviews each of the reports, papers and theses that document the details of the research results under the contracts. The critical reviews are to guide the interested reader directly to the relevant material with a minimum of searching through preliminary reports and superseded results. The review numbers correspond to the reference list in the previous section.

1. "Analysis of a Superconducting Generator for Ship Propulsion", Kutsal A. Denizmen, S.M. and O.E., May 1973. (MIT Thesis).

This thesis considers the design of a 20,000 HP generator, a piece of the drive system that has not received much attention. Denizmen produces a design for a 3600 RPM machine that is about 40" in diameter and about five feet long, with active parts weighing just over 16,000 lb.

The type of machine considered here is a "strong shield" generator, built with a warm rotor surface capable of supporting fault stresses directly. Denizmen presents a clear summary of the electrical design expressions, all of which are available elsewhere. He also presents a summary of the expressions required for calculating stresses and displacements of a thin cylindrical shell supported at the ends. A computer program was written and is presented. This program should be useful for machines of any size.

Aside from the specific machine design, there is nothing in this thesis not available elsewhere. It is clearly written and presents a good summary of the design requirements of this class of machines.

2. "Application of Superconducting Motors to Super Cavitating Hydrofoil Propulsion", John Michael Solan, S.M. and O.E., June 1973. (MIT Thesis).

This thesis was an early attempt to predict the size and elementary performance of superconducting induction motors. In it, Solan predicts a machine size, and does both steady state and transient analyses. This thesis is similar in its basic objectives to that of Rumore, although it does not succeed as well.

The design predicted is a 21,000 horsepower, 1800 RPM machine, with an outside diameter of 40" and an active length of 7.4 feet. This is consistent

with other analyses. Unfortunately, the steady state analysis is of little use because Solan chooses to plot various parameters against slip, holding torque constant. There appear to be errors in some of his dynamic simulations.

This thesis was the very first attempt to analyze this type of machine. Later investigators were more successful. In particular, Rumore covers the same ground as this thesis, with much better results.

3. "Preliminary Analysis of the Double Rotor Induction Motor", J. L. Kirtley, Jr., Electric Power Systems Engineering Laboratory (MIT), Internal Memorandum No. 23, Oct. 2, 1973.

This report is a derivation of the steady state characteristics of the dual rotor induction motor. Straightforward electric machine analytical techniques are used.

The results are useable, however there are typographical errors in the equations in the text, and these make reading difficult. The analysis is summarized in Stetkar's thesis⁽¹⁵⁾.

4. "Superconducting Electrical Machines for Ship Propulsion", J. L. Smith, Jr., J. L. Kirtley, Jr., T. A. Keim, P. Thullen, Research Progress Report to Office of Naval Research, October 15, 1973, Contract No. N0014-67-A-0204-0068.

This first progress report for the project gives the background for the research and presents the system identification study which defined the major areas of investigation. The areas were:

- (1) Rotating air-gap armature superconducting induction machine
- (2) Gas-turbine-driven superconducting generator
- (3) Multi-pole low-speed superconducting synchronous motor
- (4) Thyristor-switched superconducting motor

The status of the study in each of these four areas is described briefly. Plans for the construction of a small normally conducting model of the superconducting induction machine are discussed. A brief description is given of the design of the first experiment with the thyristor-switched motor concept.

Appended to the report are: a preliminary analysis of the superconducting induction motor⁽³⁾, Solan's thesis⁽²⁾, Denizmen's thesis⁽¹⁾, and a paper on the thermodynamic optimization of mechanical supports for cryogenic apparatus which was included later⁽¹¹⁾.

5. "Analysis and Design of Multipole Superconducting Rotating Electric Machines", Joseph Vito Minervini, S.M., January 1974. (MIT Thesis).

This thesis addresses the problem of constructing high power, low speed synchronous machines. In particular, a 40,000 HP, 120 RPM drive is considered. This is in the size and speed range required for large ships. It is thought to be difficult to build superconducting machines of this type because of the rather short pole pitch that would have to be employed.

Minervini approaches the analysis of this machine by using a cartesian geometry approximation: that is, he lays the machine out flat, ignoring curvature. This results in a simplification of the field expressions. Using this approximation, he is able to show a roughly linear dependence of power density to pole pitch, for an iron-free machine.

A machine design is estimated and compared with a conventional motor of the same rating and speed. The superconducting design has a diameter of 156 inches and an active length of about 48 inches. This is substantially smaller than the conventional machine.

Minervini also investigates the problem of starting a synchronous machine system. This is made complicated because slow pole slipping, which would ordinarily happen in starting, could produce unacceptable losses in the rotor cold space. He proposes starting at a relatively high prime mover speed, then letting the generator coast down to match motor speed.

Finally, a comparison of machine stress levels is made for a wide range of machine ratings.

This is the only analysis done for low speed machines as part of this program.

6. "Design and Construction of an Electrically Commutated AC Motor with a Fixed Torque Angle", Luis I. Cabezon G., S.B. and S.M., July 1974. (MIT Thesis).

Cabazon set out to implement Smith's idea for a thyristor-switched ac motor⁽¹⁴⁾ on a small experimental machine. This thesis is a description of that effort.

In this first experiment, great emphasis was placed on simplicity. Thyristor firing signals were derived from a set of mechanical switches and power line potential. Since, in this scheme motor speed is controlled by line potential, the thyristor gating scheme used presented the thyristors with a wide range of gate signal amplitude. In order for the scheme to work at low speed (low source voltage), the gates had to be quite sensitive. Because of this, the system was quite sensitive to noise, which could cause thyristor misfiring. A further difficulty was encountered with the mechanical commutator, which used carbon brushes. Contamination from brush wear would occasionally short commutator contacts, causing unintentional thyristor firing. This, in turn, could result in two thyristors turned on in series between two phases of the power line. This would result in catastrophic failure of the thyristors involved.

Because of the problem of inappropriate firing, this scheme never worked very well, or for very long. Cabazon did demonstrate the concept, and took some data on motor operation.

The thesis consists of a description of the thyristor-switched ac motor concept and a detailed description of the experimental setup. Some attention is paid to thyristor characteristics. There is an extensive section on experimental results, however, the real source of difficulty is not explained.

7. "Superconducting Rotating Machines", J. L. Smith, Jr., J. L. Kirtley, Jr., and P. Thullen. IEEE Trans. on Magnetics, Vol. MAG-11, No. 2, March, 1975, pp. 128-134.

This review paper presents a summary of the opportunities of and limitations on the application of superconductors in rotating electric machines of all types. The current state-of-the-art is reviewed for superconducting machines with homopolar configuration, commutated dc designs and for synchronous ac machines. All of the experimental superconducting machines which have been presented in the literature are described. Key problem areas requiring additional research are identified and several new machine

concepts are discussed. The long range potential of superconducting machines is assessed.

This paper is a non-analytical review of superconducting electric machines. It represents the state of the art in the summer of 1974, and so some of the design concepts discussed are now a bit out of date.

8. "Multipole Superconducting Electric Motors for Ship Propulsion", P. Thullen, T. A. Keim, and J. Minervini, IEEE Trans. on Magnetics, Vol. MAG-11, No. 2, March 1975, pp. 653-656.

This short paper describes the steady state analysis and rating of low speed motors, using a flat magnetic model.

This is a good condensed version of the most interesting material from Minervini's thesis⁽⁵⁾.

9. "Superconducting Electrical Machines for Ship Propulsion", J. L. Smith, Jr., and T. A. Keim, Research Progress Report to Office of Naval Research, Contract No. N0014-67-A-0204-0068, October 22, 1974.

This second progress report for the project starts with a brief review of the research. The status of the small experiment to demonstrate the principle of the superconducting induction machine is given. Progress on the demonstration of the thyristor-switched motor concept is presented briefly, and a trial design for a 20,000 HP thyristor-switched motor is summarized. Appended to the report are: Minervini's thesis⁽⁵⁾, the paper based on Minervini's thesis⁽⁸⁾, a report on the design of the air-gap armature machine experiment (later included in Stetkar's thesis⁽¹⁵⁾), Cabezon's thesis⁽⁶⁾, the details of the trial design of the 20,000 HP thyristor-switched motor (these details are not given elsewhere), and the patent application on the thyristor-switched motor, now an issued patent⁽¹⁴⁾.

10. "A Superconducting Synchronous Torque-Compensated Motor for Naval Applications", Donald M. Reynerson, S.M. and N.A., June 1975. (MIT Thesis).

This thesis is an analysis of a torque-compensated machine concept. The motivation for the use of this scheme is to eliminate the torque ordin-

arily imposed on the field winding, thus reducing the required strength and heat leak of the field winding supports. The concept described employs a stationary superconducting field winding, a stationary, normally conducting torque compensating winding, and a rotating armature.

The thesis considers only steady state conditions. It has an extensive description of the design procedure used to arrive at an example design, with an outside diameter of three feet, and a length of about six feet for a 22,700 horsepower, 1800 RPM machine. The design procedure used was a hit-or-miss affair, in which the author put a large number of sets of dimensions into a computer program, and picked the best result.

The author does not consider transient conditions such as terminal faults, and this is the major limitation of this work. One can envision several types of circumstances under which torque compensation could fail, rendering this concept useless. Ways of ensuring against compensation failure will be required before this concept can be used.

11. "Refrigeration Requirements of AC Superconducting Machines for Ship Propulsion", A. Bejan, Report to Office of Naval Research, Appendix D to Progress Report, Aug. 4, 1975, Contract No. N00014-75-C-0497.

This study establishes and documents procedures for "first order" predictions of helium cooling requirements of superconducting AC machines.

The material is presented in six chapters. Each of the first five analyzes one individual mode of heat transport to the cryogenic regions of superconducting rotors. In each case, simple numerical procedures for estimating the refrigeration requirements are presented. In addition each chapter provides design suggestions aimed at a reduced liquid helium consumption.

The individual modes of heat transport considered are:

- (1) Thermal conduction through mechanical supports
- (2) Thermal radiation across the vacuum gap
- (3) Cryogenic current leads
- (4) Eddy current heating in cylindrical shells due to time-varying magnetic fields

magnetic fields

(5) Liquid helium transfer line losses

The report concludes with an example of the use of the methods developed for estimating the liquid helium requirements. The MIT 3-MVA superconducting synchronous machine is selected for the numerical example.

12. Progress Report to Office of Naval Research, "Superconducting Machines for Ship Propulsion", Aug. 4, 1975, Contract No. N00014-75-C-0497.

This report gives the status of the work in progress as of the report date together with the work completed since the last progress report. The last experimental work with the rotating air-gap armature machine is described in this report and is not given elsewhere. The major problem was the problem of starting, or more specifically, rapid reversal of rotation with the field winding energized as would be required for a high energy superconducting field winding. The squirrel cage starting winding that was added to the synchronous field rotor of the experimental machine is described. Experiments are described which lead to the conclusion that it was not practical to start or reverse the rotation of the field rotor with the field on and the stator armature connected to a power source.

Early work by Redding on the thyristor-switched motor is reported; however, this material is superseded by Redding's thesis⁽¹³⁾.

The work by Reynerson on the torque compensated machine is summarized in the report. This work is given in complete detail in Reynerson's thesis⁽¹⁰⁾.

The work by Bejan on the refrigeration requirements of superconducting AC machines is outlined. The complete report of the experimental results is given in the final report by Bejan⁽¹¹⁾.

Appended to this report are:

- Appendix A - Stetkar's thesis⁽¹⁵⁾
- Appendix B - Reynerson's thesis⁽¹⁰⁾

Appendix C - Progress Reports by Bejan on the refrigeration requirements of superconducting AC machines.

Appendix D - Final report by Bejan⁽¹¹⁾ on the refrigeration requirements of superconducting AC machines.

13. "An SCR Commutated D.C. Motor", John A. Redding, S.M., September, 1975. (MIT Thesis).

Redding took over the thyristor-switched A.C. motor experiment after Cabezon finished with it. His major thrust was to improve the way that the thyristors were fired, thus reducing the misfiring problem, with its attendant thyristor failures.

The thyristor gating circuit developed by Redding is substantially more sophisticated than the one used by Cabezon. It involves charging a capacitor with line-line potential, and using the charge on the capacitor as the gating energy source. Auxiliary diodes and Zener diodes are used to regulate capacitor charging. In addition, gate pulse shaping and snubbing circuit elements are added.

While this new gating circuit reduces the noise sensitivity of the thyristors, it still employs a mechanical commutator as the primary signal source. Because of this, Redding's machine continues to be troubled by improper thyristor firing, with occasional thyristor failure.

The thesis contains a fairly good description of the thyristor-switched A.C. motor concept, an extensive description of the thyristor gating circuits used, several detailed tests performed on the machine, and a brief analysis of interphase commutation. Redding also makes some recommendations for future work, including an alternative arrangement for the power switching thyristors.

This document, while not well written, is reasonably well self-contained. It is possible, through reading this thesis, to understand the concept and approach taken in the development of the thyristor-switched A.C. motor. It is not necessary to read Cabezon first. The end result, however, is not yet a satisfactory machine concept.

14. "A-C Powered Thyristor Switched Electrical Motors Having Superconducting Fields", J. L. Smith, Jr., U.S. Patent No. 3,909,684, September 30, 1975.

This patent describes the type of thyristor switched motor that has been under experimental investigation during this program. The motor described comprises a multiple phase, ring-connected armature winding with switching units connected between each armature node point and a polyphase power line. Each of the switch units is made up of two thyristor bridges, one conducting current into the armature node, the other conducting out of the armature node. The switch units are controlled by a rotor position sensor to produce an armature current distribution at the proper spatial position for maximum torque production.

Taken separately, the switch units resemble a cycloconverter with as many output phases as armature node points. The motor resembles a separately excited dc machine with, of course, the commutator replaced by the switch units.

In addition to the basic machine concept, the patent describes one way of deriving the signals for gating the thyristors, employing a mechanical commutator operating at signal level. Experimental work performed on the project seems to indicate that the mechanical signal commutator is unworkable, because of contamination problems.

This drive concept is simple and promises a relatively rugged design. While it does employ a large number of power level devices, and consequently does not have a high device utilization, it does afford a high level of failure tolerance, in that failure of a few devices will not cause failure of the whole system. The use of ac lines eliminates commutation circuitry for the thyristors, and provides for rapid phase commutation in the motor.

15. "Design, Construction and Testing of an Experimental Dual-Rotor Induction Motor", J. W. Stetkar, S.M., Department of Nuclear Engineering, April, 1976. (MIT Thesis).

This MIT thesis describes our first efforts at investigating the dual rotor induction motor, one of a class of machines proposed by Smith. It was (and is) our expectation that this concept might be employed for the

construction of large motors suitable for ship drive application, with the size and weight advantages of superconducting machines but with the control characteristics of induction machinery.

Stetkar built a small experiment with a synchronous rotor concentric with an induction rotor. Because this was a first effort intended to demonstrate the concept, the experiment was not made superconducting. While there were substantial experimental difficulties, this small machine did behave essentially as expected, and demonstrated that the concept will in fact work. The small size of the experiment and the fact that it is not superconducting prevent it from properly indicating the potential of the concept.

Stetkar's thesis presents a brief theoretical analysis of the steady-state performance of machines of this class, including torque-speed and Vee curves. It then describes the design and construction in some detail. Tests described include no load voltage and short circuit current tests as a generator, and torque-speed and Vee curves as a motor. Some difficulty was encountered in starting the synchronous rotor and this is described. Experimental difficulties caused by an inadequately designed induction rotor, along with a fix, are described.

This thesis is a good description of the experiment, but it is not an effective presentation of the concept that experiment was intended to demonstrate.

16. "The Rotating Air Gap Armature Machine as a Superconducting Induction Motor for High Speed Ship Propulsion", Frank C. Rumore, S.M., August, 1976. (MIT Thesis).

This thesis is a theoretical study of the dual rotor superconducting induction motor. The thesis is divided into three parts: a steady-state model, an electrical design of a high speed motor, and a dynamic study. Of these, the electrical design is the most valuable.

The steady-state model section is Rumore's attempt to model the steady-state operation of the machine. His results are valid and readily applicable, although he does not follow the usual sign conventions, so that his analysis

may be confusing.

The electrical design section uses basic machine design expressions and the steady-state analysis to arrive at an electrical design criterion. Rumore uses a novel, innovative approach to machine design, employing a sophisticated computer program to do manipulations, computations and graphics. Part of the output of the electrical design program is a picture representing voltage and current phasors over a range of machine output. A 1200 RPM preliminary motor design is presented, with an outer diameter of one meter, and a rating of 11 MVA. Meter of active length.

The dynamic simulations presented represent the effects of terminal faults on the machine.

This thesis is very well written and presents a good picture of the superconducting induction motor. It is aimed primarily at pod-mounted, high speed motors, for which it presents an optimistic result.

17. "An Improved Design of a SCR Commutated D.C. Motor", J. Frederick Donohoe, S.M., February, 1977. (MIT Thesis).

This thesis describes the third attempt at MIT at building a thyristor switched ac motor. The drive system developed has operated successfully for many hours.

This drive system utilizes an optical rotor position sensor, a phase comparator for determining the state of line voltages, a high frequency clock for generating gating signals, digital logic gates for determining proper thyristor gating signals, and pulse transformers for gating the thyristors.

The drive system produced presents characteristics similar to those of a separately excited dc motor. Some performance curves are given for a small experiment. In addition, a larger, superconducting is described, although it had not been tested at the time this thesis was written.

A brief qualitative description of commutation and speed limitation is given.

This thesis gives a good description of the specific electronic

circuitry built for the thyristor switched motor. Its description of the motor concept itself is rather brief and qualitative.